

Maryland Sand, Gravel & Stone
Remediation Technology Screening

Technical Memorandum

June 2001

Revised 4 January 2002

48410.23.01

Environmental Resources Management
2666 Riva Road, Suite 200
Annapolis, Maryland 21401



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Investigations conducted at the Maryland Sand Gravel and Stone (MSG&S) site in Elkton, Maryland identified three major areas as "principal threat" material requiring treatment: the Northern Depression Area (NDA), the Buried Waste Area (BWA), and Pond 02 Wet Area (Figure 1). The Contaminants of Concern (CoC) which present a potential principal threat in soil and ground water in each of these areas are all volatile organic compounds (VOCs). The CoC are listed in Table 1.

Two *in-situ* technologies and one *Ex-situ* technology have been identified as being potentially applicable for treatment of the principal threat soil and will be evaluated in greater detail in the revised Focused Feasibility Study (FFS) for Operable Unit 3 (OU3). These candidate technologies are:

- *In-situ* chemical oxidation with mixing
- *In-situ* thermal treatment (resistive heating and/or steam)
- *Ex-situ* low temperature thermal desorption

The May 1999 draft FFS for OU3 identified *in-situ* chemical oxidation as the representative *in-situ* treatment technology. Low temperature thermal desorption (LTTD) was identified in the FFS as the representative *ex-situ* treatment technology. EPA comments on the draft FFS included a brief discussion for potential consideration of *in-situ* thermal treatment technologies, specifically six-phase electrical resistive heating (SPH). In March 2001, the draft FFS was revised to include an evaluation of several *in-situ* and *ex-situ* treatment alternatives, including LTTD, SPH, steam treatment, and *in-situ* chemical oxidation.

In an effort to further assess the applicability of each of these treatment technologies, and the viability of each technology for pilot testing at the MSG&S site, additional site-specific data was needed. A Remediation Technology Screening Investigation Work Plan was submitted to EPA in February 2001, and comments were subsequently received from EPA and MDE during several telephone communications and electronic mail received on 6 March 2001. An addendum to the work plan addressing the agency comments was submitted on 14 March 2001.

The intent of this supplemental investigation was to obtain the qualitative testing data needed for remedy screening, including laboratory treatability testing for chemical oxidation. The results of this investigation will be incorporated into the final FFS to support the selection of alternatives for the site. As discussed in the work plan, an innovative

Figure 1
Sample Locations for
Remediation Technology Screening Investigation
Maryland Sand, Gravel, and Stone
Elkton, Maryland

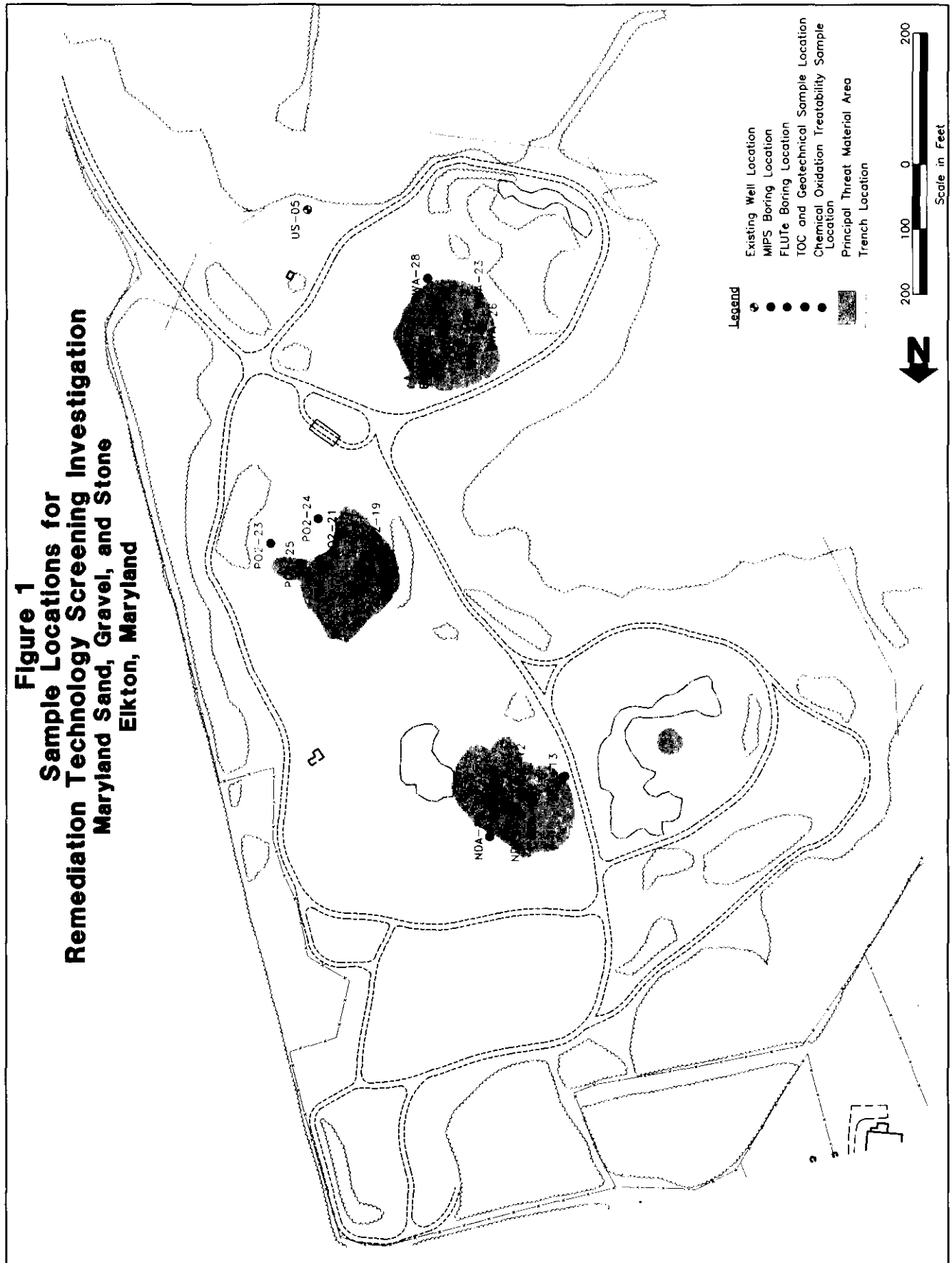


Table 1 *Constituents of Concern for Remediation Technology Evaluation*
Maryland Sand, Gravel, & Stone, Elkton, Maryland

Volatile Organic Compounds	Observed Range in Principal Threat Areas (mg/kg)						PT ^(a)
	NDA		P02		BWA		
	Max	Sample Location/Depth ^(b)	Max	Sample Location/Depth ^(b)	Max	Sample Location/Depth ^(b)	
Benzene	2300	NDA-02/8	130	P02-SS02W/0	30	BWA-01/16.5	7
Methylene chloride	1700	NDA-02/8	550	P02-04/7.5	58	BWA-01/16.5	9
Tetrachloroethene	110000	NDA-02/8	7900	P02-SS02W/0	2000	BWA-01/16.5	25
Trichloroethene	14000	NDA-02/8	3000	P02-SS02W/0	1000	BWA-01/16.5	36
Vinyl chloride	0.029	NDA99-04/6	0.97	P02-01	0.015	BWA-13/19	0.9
Chlorobenzene	270000	NDA-02/8	11000	P02-SS02W/0	3000	BWA-01/16.5	249
Chloroethane	2850	NDA-02/8	440	P02-SS02W/0	15.5	BWA-01/11	82
1,2-Dichloroethane	1.6	NDA-03/17.5	2.4	P02-05/12	2.05	BWA-10/22	2.7
1,1-Dichloroethene	178	NDA99-05/14	12	P02-01/11	15	BWA-01/16.5	1817
Cis-1,2-Dichloroethene	2850	NDA-02/8	440	P02-SS02W/0	15.5	BWA-01/11	139
Total 1,2-Dichloroethene ^(c)	2850	---	440	---	15.5	---	125
Acetone	4400	NDA-02/12.2	610	P02-SS02W/0	12	BWA-01/11	1386
Methyl isobutyl ketone	4400	NDA-02/12.2	520	P02-SS02W/0	370	BWA-01/16.5	318

NDA: Northern Depression Area; P02: Pond 02 Depression; BWA: Buried Waste Area; PT: Principal Threat

a) PT = Calculated principal threat criteria concentrations.

b) Depth is in feet below ground surface

c) Total 1,2-Dichloroethene is the sum of the concentrations of the cis- and trans- isomers

The maximum sample concentration reflects the maximum concentrations observed in soil in each of the three principal threat areas, not including soil samples that contained waste-like material.

technology that shows favorable results in the screening investigation may be considered in the final FFS, subject to further testing in the remedial design phase. Subsequent bench scale and pilot testing of one or more of these technologies may be required during the remedial design phase, to further compare promising technologies. The scope of any pilot tests would be presented in separate work plans.

The supplemental investigation activities were designed for the collection of data necessary for the initial screening evaluation of two potential remedial technologies: *in-situ* chemical oxidation and thermal treatment. Thermal treatment technologies that will be considered and evaluated in the final FFS include both *in-situ* technologies (e.g., SPH, steam (dynamic underground stripping [DUS], or RF heating), and *ex-situ* technologies (e.g., low-temperature thermal desorption [LTTD]). Chemical oxidants that may be considered for the final FFS include potassium permanganate and sodium persulfate. The data from the supplemental investigation included chemical and physical analyses of soil samples in the three primary "principal threat" areas of the site, as well as laboratory bench-scale testing of potential oxidants.

A review of published reports was conducted to identify case studies of the various thermal and chemical oxidation remedial technologies being considered for the MSG&S site. The case studies are summarized in Table 2.

Table 2 Selected Case Study Comparison
Maryland Sand, Gravel, and Stone
Elkton, Maryland

Site Name	Location	Media	COCs	Type of Unit	Treated Volume	Initial Conc. (max)	Final Conc. (Removal Efficiency) (Clean-up Goals)	Treatment Cost	Notes
The Southern Maryland Wood Treatment Site	Hollywood, MD	soil and sediment	PCP Creosote PAHs phenols	Two CTDUs (Continuous Thermal Description Units)	270,000 tons 11-16 tph 10 min. residence time	NAPL	Residential Cleanliness Standards	\$220/ton	-total project cost: \$61 million -original soil volume estimate: 140,000 tons; volume treated = 270,000 tons
Lockheed Martin Astronautics	Littleton, CO	—	VOCs PCBs	LITTD run 24 hrs/7 days	21342 tons ~ 14tph	TCE: 2150 ppm	TCE = 0.091 mg/L TCLP Xylene = 28 ppm PCE = 0.05 mg/L TCLP Toluene = 0.33 mg/L TCLP 1,1,1-TCA = 0.41 TCLP (clean-up levels)		-Soil treated by the thermal desorber met clean-up goals, but initial concentrations were lower and clean-up levels were higher than for MSG&S
Letterkenny Army Depot	Chambersburg, PA	Gravel Clay with Sand 15 % Coarse sand or larger 70 % silt and clay 24% avg. moisture content	TCE PCBs Metals	LITTD	13,986 cy/d	TCE: 30,000 ppm Metals: 1-150 ppm	TCE = 0.05 mg/kg Soils were required to meet Land Disposal Restriction Treatment Standards (clean-up levels)	\$220/cy/d	- During demonstration tests emissions levels were exceeded and treatment levels for TCE were not achieved - A dry scrubber was added to the unit to meet emissions requirements. - The residence time for certain black stained materials increased from 60 min. to 150 min. to reach treatment levels. - 10% of the clay and 14 % of the black stained material had to be re-treated in order to reach clean-up levels.
Waldick Aerospace Devices	Wall Township, NJ	Sand with some silt, clay, and gravel	BTEX VOCs	LITTD	3,450 cy/d ~ 20 tph	PCA: 26 ppm PCE: 160 ppm	Total VOCs = 1.0 ppm (clean-up level)	\$885/y/d.	- The unit did not meet air emissions standards during the performance testing. - Soil treated by the thermal desorber met clean-up goals
American Thermostat	South Cairo, New York	~ 8 acres	TCE PCE	LITTD (direct-contact rotary dryer)	62,400 tons Phase I: 20,800 tons (13,000 cy/d) Phase II: 48,000 tons (30,000 cy/d) max. feed rate: Phase I: 22 tph Phase II: 50 tph	TCE: ND (phase I) 3.5 ppm (phase II) PCE: 126 ppm (phase I) 66 ppm (phase II)	TCE: ND (phase I) 0.019 ppm (phase II) PCE: 0.033 ppm (phase I) 0.12 ppm (phase II) (achieved levels)	Phase I: \$51.74/ ton -Total Cost for Phase I: \$3.77 million -Total Cost for Phase II: \$6.54 million Phase II: \$34.38/ ton	- Residence time = 7-8 minutes - Total Cost for Phase I: \$3.77 million - Total Cost for Phase II: \$6.54 million
Savannah River Site (demonstration)	Aiken, South Carolina	Thick section of relatively permeable sands contaminated target zone = 10' thick layer of clay @ 40'	TCE PCE	SFSH		TCE: 181 ppb PCE: 4529 ppb	- 99.7% removal within electrode array - 93% removal at a distance of 8' from the array	\$88/cy/d	-Cost assumes a contaminated site 100' in diameter and 20 - 120 feet deep with a remediation time of 5 years.
Confidential Manufacturing Facility	Skokie, Illinois	Heterogeneous silty sands with clay lenses to 18' bgs underlain by dense clay till aquitard Depth to GW = 7 bgs	TCE TCA DCE	SFSH	34,600 cy/d	TCE: 130 mg/L (max) 54.4 mg/L (avg) TCA: 150 mg/L (max) 52.3 mg/L (avg) DCE: 160 mg/L (max) 37.6 mg/L (avg)	TCE: 17.5 mg/L TCA: 8.85 mg/L DCE: 35.5 mg/L (clean-up levels)	\$32/cy/d	- Groundwater concentrations reduced by: -more than 99% for TCE (54.4 to 0.4 mg/L) -more than 99% for TCA (52.3 to 0.2 mg/L) -more than 97% for DCE (37.6 to 0.8 mg/L)
Canadian Forces Base (demonstration)	Borden, Ontario	50 x 50 meter site atop a 4 meter thick highly homogeneous, sand aquifer. Source zone located 1 meter below the water table	TCE PCE	Chem-Ox (KMnO4)		TCE: 1,200 mg/kg PCE: 6,700 mg/kg	-99% reduction in peak concentrations	-total cost of \$45,000	-Source zone flushed with a solution of ~ 8g/L KMnO4 for almost 500 days.
Kansas City Plant	Kansas City, MO		TCE DCE chloroethane	Chem-Ox (KMnO4)	60 x 40 foot area	TCE: over 15,000 ppb DCE: over 15,000 ppb Chloroethane: over 1,500 ppb	-83% TCE removal from unsaturated zone - 69% TCE removal from saturated soil	\$128/cy/d total cost: \$1 million	-The goal of the project was only a 70% contaminant removal rate.
Launch Complex 34	Cape Canaveral, FL	gray fine sand and shell fragments to silty/clayey sands	TCE	Chem-Ox (KMnO4)	6,250 cubic yds	5,039 kg of DNAPL	removed 5,022 kg of DNAPL	\$181/cy/d	- ~163 lbs. of KMnO4 were injected over a period of 61 days.
Alameda Point	Oakland, CA	sandy silty fill, then fine grain silty sand	TCE	SFSH	5000 cubic yds	10,500 kg DNAPL	removed 2,000 kg DNAPL	\$102/cy/d	-The lack of a vadose zone and major storms affected treatment efficiency
Portsmouth Gas Diffusion Plant	Portsmouth, Ohio	days and silts atop of a relatively permeable aquifer, underlain by shale	TCE	Steam Stripping	120 x 180 foot area 19 wells	550 kg of TCE	-115 kg of TCE removed (~80% removal efficiency)	—	-Permanganate oxidation was used at this site without success.

The February 2001 work plan, and 14 March 2001 Addendum, included bench-scale laboratory treatability studies for the evaluation of *in-situ* chemical oxidation. Laboratory testing for the evaluation of *in-situ* thermal treatment was deferred. Field-testing included additional activities associated with source-area characterization. Specifically, additional characterization of each of the three ground water principal threat areas (i.e., NDA, BWA and Pond 02) was performed.

DATA COLLECTION

Between 13 March and 20 April 2001 ERM subcontracted Tidewater, Inc. and Columbia Technologies, Inc. to assist in the advancement of soil borings in and around each of the three principal threat areas. Site data and media samples were collected for the thermal treatment and chemical oxidation technology evaluation.

Membrane Interface Probe System

Within and adjacent to each of the three principal threat areas, two additional continuous borings (NDA-12 and NDA-13, BWA-27 and BWA-28, and P02-24 and P02-25) were advanced with the direct-push rig for *in-situ* vertical profiling (Figure 1). The vertical profiling utilized a soil conductivity probe and a membrane interface probe system (MIPS). The MIPS provided a continuous field screening measurement of total volatile organic compounds (VOCs) from an electron capture detector (ECD), a photoionization detector (PID), and a flame ionization detector (FID) that are housed in the probe. A continuous log was generated for the entire vertical profile of the boring for soil conductivity (in mS/M), FID response (in mV), PID response (in mV), ECD response (in mV), and temperature in degrees Celsius (°C). The temperature profile was used as an indicator of soil moisture content, and helped to identify the depth of the static water table.

Two soil samples (BWA-27, 4 feet and 11 feet) were also collected using EPA Method 5035 and analyzed for VOCs by CLP Method OCLP OLM03.1 for use in comparison to the MIPS *in-situ* profile data. These selected soil samples were shipped by overnight courier to the designated laboratory, STL-Dayton, for analyses.

FLUTe™ Ribbon NAPL Sampler

Another innovative technology called a Ribbon NAPL Sampler (developed by Flexible Liner Underground Technologies, a.k.a. FLUTe™) was tested and applied during this investigation. The technology was recently tested at the Department of Energy's Savannah River Site (SRS) and at NASA's Cape Canaveral facility. This technology involves the use of an inflated membrane liner (i.e., polyethylene fabric that is similar or equivalent to Tyvek™) coated on one side with a three colored hydrophobic dyes that was inserted into an open borehole. The hydrophobic dye is only sensitive to non-aqueous phase liquids (NAPL) which will wick the dye through the membrane leaving bright red, blue or black stripes when in contact with hydrophobic product.

The purpose of the application of the Ribbon NAPL Sampler was to assess whether any free-phase product exists in the identified principal threat areas. For this investigation, the Ribbon NAPL Sampler was deployed in at least one borehole (NDA-11, BWA-26, and P02-22 and P02-23) from each of the 3 principal threat areas (Figure 1). The Ribbon NAPL Sampler was inflated with tap water in the borehole such that the membrane was in direct contact with the wall of the borehole. It was then removed from the borehole using an internal tether that prevented smearing of the membrane on extraction. After the membrane was removed from the borehole, it was examined for visual indications of the presence of presence of any NAPL throughout the full length of the borehole.

Soil Samples for Geotechnical Analyses

In addition to MIPS and FLUTe™ profiling in the source areas, the supplemental investigation included the collection of soil samples for geotechnical characteristics. Soil samples were collected from the Northern Depression Area (NDA-09 and NDA-10), the Buried Waste Area (BWA-24 and BWA-25), and the Pond 2 Depression (P02-20 and P02-21) (Figure 1). Two borings were advanced in each of these three principal threat areas, at five-foot depth intervals until the basal clay underlying the Upper Sand was encountered. The samples were collected using direct-push drilling with 2-inch diameter, thin-walled acetate sleeves. The soil samples from each boring were analyzed for total organic carbon (TOC) content and for selected geotechnical parameters, including grain-size distribution, moisture content, density, and Atterberg limits. The geotechnical analyses were performed by EBA Engineering Inc. and the TOC analyses were performed by STL Inc.

Soil Samples for Chemical Analyses

Between 13 and 20 March 2001 ERM collected representative soil samples from the three major principal threat locations: NDA, BWA, and Pond 02. Soil from each location was collected and sent to the ERM's Remediation Technology Center (RTC) for use in the study. One boring was placed to the basal clay in each of the three principal threat areas as follows:

- Northern depression area - NDA-08 located immediately adjacent to the boring NDA-02;
- Buried waste area - BWA-23 located immediately adjacent to the boring BWA-01; and
- Pond 02 depression - P02-19 located immediately adjacent to P02-01.

The samples were collected using direct-push drilling and 2-inch diameter, thin-walled acetate sleeves. The soils were packed in one-liter, amber, wide-mouth glass jars with Teflon cap liners. To characterize unsaturated soils the depth to the water table was equally divided into five intervals and one jar was collected from each interval. Next, the depth from the water table to the basal clay was equally divided into five intervals and one jar was collected from each of these intervals to characterize saturated soils. The soil samples were handled to minimize contact with air and the jars were filled with minimal headspace.

Several soil samples were also collected and analyzed at the designated laboratory (STL-Dayton) for VOCs, for use in comparison to the MIPS *in-situ* profile data. These selected soil samples were used to provide us with a correlation between the field profiling data and the actual measured VOC content of the soil.

Soil Samples for Metals Analyses

Soil samples were collected from each of the three major principal threat areas for analysis of total and leachable metals by the EPA Toxicity Characteristic Leaching Procedure (TCLP). The soil samples were collected from locations where previous samples identified soil with elevated metals concentrations. Two samples were collected in the NDA. One sample was collected from the BWA and one from the Pond 2 Wet Area. One of the NDA samples was also analyzed for thallium to assess the reliability of a high thallium result reported in a previous investigation for sample NDA-02 (10'-12'). The previous sample was analyzed using field analytical methods.

Ground Water Samples for Chemical Analyses

On 4 April 2001 ERM collected a ground water sample from well US-05, which has historically had some of the highest concentrations of dissolved metal analytes in site ground water, to test the effect of *in-situ* oxidation on metals in the ground water. A new disposable polyethylene bailer was used to purge three well volumes from the well. Twenty liters of ground water was then collected without headspace in five 4-liter amber glass bottles with Teflon lids. The water samples were delivered on ice to the RTC.

The supplemental investigation also included limited aquifer testing of selected wells in the principal threat areas. The testing included single well pumping tests, and slug tests, to derive point-specific aquifer parameters.

3.0 DATA SUMMARY

3.1 SOURCE AREA CHARACTERIZATION

3.1.1 *FLUTe™ Ribbon NAPL Sampler*

For this investigation, a Ribbon NAPL Sampler was deployed in four boreholes (i.e., NDA-11, BWA-26, and P02-22 and P02-23) located within each of the 3 principal threat areas (Figure 1). The Ribbon NAPL Sampler confirmed the presence of NAPL at two locations: NDA-11 and BWA-26. Neither of the two targeted locations within the Pond 02 Wet Area showed evidence of non-aqueous phase hydrocarbons.

To confirm that the constituents present at the site would react with the hydrophobic dye used on the membrane a section of membrane was forwarded to RTC for testing. The solvents and mixtures tested with the membrane included: chlorobenzene, 2-dichlorobenzene, 1,3-dichlorobenzene, benzene, toluene, xylenes, distilled water, and distilled water that had been spiked with all of the previously mentioned organic compounds and several chlorinated solvents). Results of RTC's testing indicated that the membrane itself appeared to be hydrophobic. Distilled water and distilled water spiked with organic compounds did not "wet" the membrane whereas the neat organic materials tested did "wet" the fabric. When the membrane was in contact with each of the organic compounds tested the colored dye stripes were wicked through the membrane and bleeding of the colored lines could be seen (Figure 2). Distilled water and distilled water spiked with organic compounds had no bleeding affect on the dye-impregnated membrane.

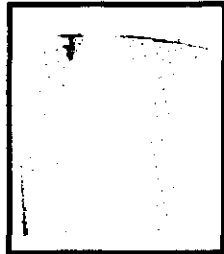
NDA-11 Observations

NAPL observed on the Ribbon Sampler at NDA-11 was characterized as slightly viscous, amber colored, and oily to touch. The NAPL reacted with the membrane by wicking the colored stripes through the membrane and towards the edges of the NAPL. Two distinct zones with product, 9 to 12 feet below ground surface (bgs) and 18 to 20.5 feet bgs were observed in the sands above the water table. There were no discernable zones of NAPL beneath the water table; however, small globules (< 3-inches) and trace dots (< 0.5-inches) of NAPL were observed throughout the borehole down to the basal clay unit. The NDA-11 boring log with corresponding photographs of the Ribbon Sampler is included in Appendix A.

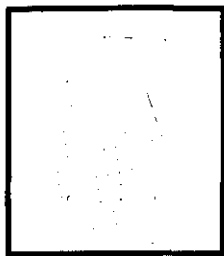
Figure 2 Laboratory Testing of FLUTe Ribbon NAPL Sampler ^(a)
Maryland Sand, Gravel, and Stone
Elkton, Maryland



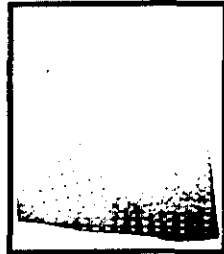
Distilled Water



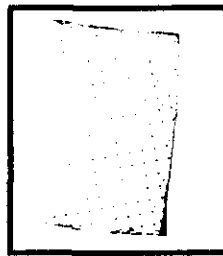
Benzene



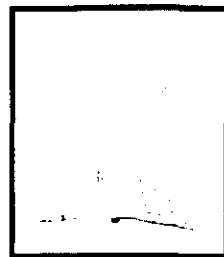
**Distilled Water
Spiked with Organics**



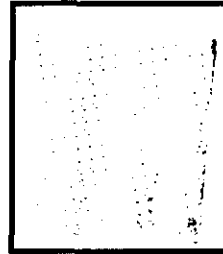
Chlorobenzene



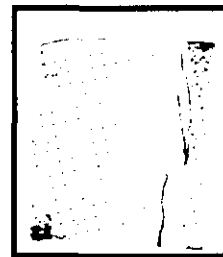
1,2-Dichlorobenzene



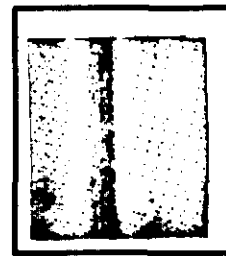
Toluene



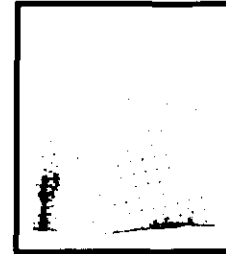
**DNAPL ^(b)
(Example Mixture)**



Xylene



1,3-Dichlorobenzene



MIBK

a) Each sample subjected to contact with listed solvent or solution for a period of one hour

b) Mixture solution of carbon tetrachloride, methylene chloride, and chloroform (not from MSG&S site)

BWA-26 Observations

Inspection of the Ribbon Sampler at BWA-26 indicated the presence of a non-viscous, light brown-colored NAPL. The NAPL reacted with the membrane by wicking the colored stripes through the membrane and towards the edges of the NAPL. There were no distinct zones of product observed; however, several globules (< 3-inches) and dots (<0.5-inches) of NAPL were observed above the water table between 11 and 13.5 feet bgs. The location of the NAPL appears to be coincident with clay and silt layers immediately above the water table. The BWA-26 boring log with corresponding photographs of the Ribbon Sampler is included in Appendix A.

3.1.2 *Membrane Interface Probe System (MIPS)*

The MIPS data was used to assess the horizontal and vertical extent of contamination in the soil and ground water, as well as, determine if there was any correlation between contaminant location and lithologic unit. Appendix B contains the MIPS profiles for the six borings completed at the site.

Northern Depression Area

One MIPS boring, NDA-12 was located within the principal threat area approximately 30 feet down gradient of the FLUTE™ borehole location. The MIPS profile for NDA-12 indicated that the bulk of the contaminants were chlorinated VOCs and were concentrated between the intervals of 4 to 9 feet bgs and 17 to 23 feet bgs. There was very limited response on the FID and PID; however, the ECD instrument was at its maximum response during much of these soil intervals. Two small spikes were observed on the ECD beneath the water table at 35 feet and 44 feet bgs. Although trace amounts of NAPL were indicated below the water table on the FLUTE™ from boring NDA-11, dissolved concentrations of chlorinated VOCs in deep wells TMW-1 (completed in soil boring NDA-08) and TMW-2 (completed in soil boring NDA-09), both of which are screened from 39 to 44 feet bgs, were two to three orders of magnitude less than those reported for shallow well TMW-2S (adjacent to boring NDA-09) (ERM, December 2001). Therefore, the ECD responses at depth do not appear to correspond to any source of major impact to ground water quality. The soil conductivity probe also showed a sharp increase in conductivity between 18 and 22 feet possibly indicating the presence of silt or clay layer.

The second MIPS boring, NDA-13, was virtually clean (i.e., free of any ECD/FID/PID response) with the exception of a 2 foot interval

immediately above and below the water table. Although the soil conductivity probe indicated an increase in silt and clay content, a distinct lithologic transition was not observed at this location.

Buried Waste Area

One MIPS boring, BWA-27 was located within the principal threat area approximately 30 feet northeast of FLUTe™ borehole location. The MIPS profile for BWA-27 indicated that the bulk of the contaminants were chlorinated VOCs and were concentrated between the intervals of 6 to 16 feet bgs. There was very limited response on the FID and PID; however, the ECD instrument was at its maximum response during much of this soil interval. The soil conductivity probe also showed a steady increase in conductivity between 6 and 22 feet indicating an increase of silt and clay relative to fine sand. The ECD indicated that limited VOC contamination in ground water exists beneath the water table to the bottom depth of the borehole at 27.5 feet bgs. The BWA-26 FLUTe™ results showed no visual evidence of NAPL beneath the water table on the FLUTe™ liner. In addition, dissolved VOC concentrations at deep well TMW-6 (ERM, December 2001), which is approximately 30 feet from boring BWA-26, are notably lower than in the corresponding shallow well (TMW-6S).

The second MIPS boring, BWA-28, was virtually clean (i.e., free of any ECD/FID/PID response) throughout the entire borehole interval. The soil conductivity probe indicated a gradual increase in silt and clay content, and a distinct lithologic transition from sand to clay at 20 feet bgs.

Pond 02

Two borings, P02-24 and P02-25, were located on the fringe of the principal threat area. The MIPS profiles for the two borings were very similar. The ECD indicated that the bulk of the VOC response was concentrated between the intervals of 6 to 14 feet bgs suggesting VOC contamination is present within the ground water table smear zone and decreasing substantially with depth. There was very limited to no response on the FID and PID instruments. The soil conductivity probe also showed a steady increase in conductivity between 6 and 14 feet with increasing silt and clay. A distinct lithologic transition from sand to clay was not encountered in either boring. It is not unusual to have little or no change in soil conductivity where the sand and clay are composed of the same material, silica.

In summary, the data gathered by the MIPS profiling provided information useful for delineation of the horizontal and vertical extent of contamination at the three principal threat areas. The MIPS data indicated

that the bulk of the contamination appears to be above the water table in the principal threat areas and within the ground water table smear zone outside of the principal threat areas. Also, VOCs at the site appear to be held within discrete silt and clay lenses and is more quickly attenuated in the sand layers.

3.1.3 Chemical Analyses

Two soil samples, BWA-27 (4 feet and 11 feet), were analyzed for VOCs at the designated laboratory (STL-Dayton) for use in comparison to the MIPS *in-situ* profile data. The 4 feet sample was collected from a sand layer and the 11 feet sample was collected from a silty clay layer. Each sample was targeted for a soil interval displaying a moderate to high response on the ECD. The following table summarizes the relative response (mV) of the FID, PID and ECD detectors along with the total BTEX and chlorinated VOC concentrations (mg/kg) reported by the analytical laboratory.

MIPS/VOC Comparison Soil Samples

Analysis	BWA-27, 4 feet (Sand)	BWA-27, 11 feet (Silt and Clay)
FID (mV)	21,000	3,600,000
PID (mV)	46,000	950,000
ECD (mV)	3,500,000	12,800,000 *
Total BTEX (mg/kg)	0	38.7
Total CVOCs (mg/kg)	33.4	91.7
Total VOCs (mg/kg)	34.0	171.0

Total BTEX - sum of benzene, toluene, ethylbenzene and xylene concentrations.

Total CVOCs - sum of eight detected chlorinated VOC concentrations.

Total VOCs - sum of all constituents detected in Method OLM03.1 analysis

*The maximum ECD instrument response was limited to 12,804,991 mV.

3.2 SOIL SAMPLES FOR METALS ANALYSES

The total and TCLP analytical results are presented in Table 3. The results indicated that the leachable metals concentrations in the soil samples are below TCLP regulatory levels for hazardous waste identification. Thallium was not detected in the NDA sample.

Table 3 RCRA Metals Sample Results
Maryland Sand, Gravel, & Stone
Elkton, Maryland

Parameter	Units	Reporting Limit	Maryland Standards	Region III RBC	NDA - 08 (12 - 13')	BWA - 23 (10 - 12')	NDA - 10 (12 - 14')	NDA - 10 (12 - 14') (Dup)	PO2 - 19 (10 - 12')
Arsenic	mg/kg	2.4	6.2	3.8	0.87 B	1.2 B	2.4 B	3.3	1.1 B
Barium	mg/kg	0.042	1500	140000	5.5 B	7 B	14.7 B	15.9 B	5 B
Cadmium	mg/kg	0.066	21	1000 a	4.1	0.86 B	0.067 U	0.075 U	0.68 B
Chromium	mg/kg	0.33	62	6100 b	20.2 *	18.3 *	35.4 *	44.7 *	22.2 *
Lead	mg/kg	0.71	400	400 c	35.1 *	26 *	5.2 *	7.6 *	21.2 *
Selenium	mg/kg	1.2	100	10000	0.99 U	0.97 U	1 U	1.1 U	1 U
Silver	mg/kg	2.4	100	10000	0.35 U	0.35 U	0.36 U	0.4 U	0.37 U
Mercury	mg/kg	0.12	0.12	610 d	0.064 B	0.058 U	0.06 U	0.21	0.061 U
Thallium	mg/kg	2.4	1.5	140	1.9 U	NA	NA	NA	NA

Samples collected 13-20 March, 2001

IDL = Instrument Detection Limit B = result is between IDL and RL

U = result is less than the IDL NA = not analyzed for

a) Cadmium-water used as surrogate for Cadmium RBC

b) Chromium VI used as surrogate for Chromium RBC

c) EPA OSWER Guidance was used for the soil RBC value.

d) Mercuric Chloride used as surrogate for Mercury RBC

TCLP Metals Sample Results
Maryland Sand, Gravel, & Stone
Elkton, Maryland

Parameter	Units	Reporting Limit	Regulatory Limit	BWA - 23 (10 - 12')	NDA - 08 (12 - 13')	NDA - 10 (12 - 14')	NDA - 10 (12 - 14') (Dup)	PO2 - 19 (10 - 12')
Arsenic	mg/L	0.5	5	ND	ND	ND	ND	ND
Barium	mg/L	10	100	0.31 B	0.11 B	0.083 B	0.087 B	0.074 B
Cadium	mg/L	0.1	1	0.053 B	0.15	0.00064 B	0.00043 B	0.002 B
Chromium	mg/L	0.5	5	0.015 B	0.0087 B	0.0031 B	0.0026 B	0.012 B
Lead	mg/L	0.5	5	0.54	0.11 B	0.013 B	0.016 B	0.073 B
Selenium	mg/L	0.25	1	0.0085 B	0.0086 B	0.0076 B	0.0068 B	0.0086 B
Silver	mg/L	0.5	5	ND	ND	ND	ND	ND
Mercury	mg/L	0.002	0.2	ND	ND	ND	ND	ND

Samples Collected 13-20 March, 2001

ND = Not Detected

B = Estimated Result. Result is less than the Reporting Limit.

Results for the geotechnical samples are summarized in Table 4, and briefly described below.

Northern Depression Area - Samples collected from NDA-09, located on the mound, and NDA-10, located immediately behind the mound were primarily sand and silt mixtures. The average laboratory measured moisture content was 13 percent (mass). Only one sample, NDA-10 10-14 feet, was submitted for Atterberg limits. The sample was classified as an inorganic silty clay with low plasticity and a moisture content of 20 percent (mass). The average bulk density was 92 lbs./ft³ for the soils.

Buried Waste Area - Samples collected from BWA-24 and BWA-25, located on the perimeter of the principal threat area, indicated the soils were primarily silty sand to clayey sand mixtures with an average laboratory measured moisture content of 14 percent (mass). All but one sample was submitted for Atterberg limits. These soils were found to have a low plasticity. The average bulk density for the soils was 105 lbs./ft³.

Pond 02 - Samples collected from Pond 02 Wet Area, P02-20 and P02-21, located near the perimeter of the principal threat area, indicated the soils were primarily silty sands with increasing clay at depth. The average laboratory measured moisture content was 16 percent (mass). Seven of the nine samples were submitted for Atterberg limits. These soils were found to have a low plasticity. The average bulk density for the soils was 106 lbs./ft³.

Total Organic Carbon

Two borings were completed in each of the site's three principal threat areas to measure for total organic carbon (TOC) content. A summary of these results is presented in Table 5.

Samples were analyzed from the NDA from boring locations NDA-09 and NDA-10. The TOC values ranged from not detected (ND) to 6,300 mg/kg (0.63%). The high value obtained from the NDA-09 sample at 20 feet may be correlated with the presence of free-phase organic product that has been identified at that location in FLUTe testing.

The samples used to characterize the BWA were obtained from the BWA-24 and BWA-25 boring locations. TOC values in this area ranged from 780 mg/kg (0.08%) near the ground surface to ND at 12-16 feet. In general, the TOC values for this area were depleted near the water table.

Table 4 **Geotechnical Results (Revised 10/4/2001)**
Maryland Sand, Gravel, and Stone Site, Elkton, Maryland

Sample No.	Depth (ft)	Moisture		Percent		Liquid Limit	Plastic Limit	Plastic Index	Tube		USCS Classification	Estimated Hydraulic Conductivity ¹	
		Content (%)	Passing No. 200 Sieve	Limit	Limit				Density (pcf)			(cm/sec)	
NDA-09	0-5	14	26.1	16.0	NP	NP	NP	NP	72.10		SM	1.28 E-05	
	5-10	15.6	4.1	NP	NP	NP	NP	NP	80.30		SP	1.30 E-02	
	10-15	9.4	15.2	NP	NP	NP	NP	NP	89.40		SM	1.71 E-03	
	15-20	13.6	23.4	NP	NP	NP	NP	NP	76.40		SM	1.31 E-04	
NDA-10	5-10	12.2	15.3	NP	NP	NP	NP	NP	97.90		SM	2.58 E-04	
	10-14	20.2	18.9	25.0	15	7.00			95.80		CL-ML	1.68 E-07	
PO2-20	0-5	9.5	15.8	NP	NP	NP	NP	NP	106.30		SM	2.16 E-03	
	5-10	14.7	12.6	18.0	15	3.00			112.40		SM	2.74 E-04	
	10-15	12.5	17.7	20.0	NP	NP			123.30		SW-SM	6.91 E-03	
PO2-21	0-5	19	64.7	24.0	17	7.00			89.20		SC-SM	1.09 E-05	
	5-15	14	28	22.0	18	4.00			105.20		SC-SM	8.74 E-05	
BWA-24	0-5	10.8	31.6	25.0	18	7.00			100.00		SC-SM	4.20 E-06	
	5-10	11.5	32.1	25.00	18	7.00			111.00		SC-SM	2.32 E-05	
	10-15	13.6	27	24.0	21.00	3.00			102.50		SM	2.69 E-05	
BWA-25	0-10	9.8	32.2	25.0	18	7.00			116.30		SC-SM	2.27 E-06	
	11.5-12	10.5	30.8	22.0	17	5.00			112.10		SC-SM	3.31 E-06	

Samples collected by ERM 13-20 March, 2001

Source: EBA Engineering, Inc. - May 2001

¹ - Hydraulic conductivity estimated from grainsize analysis using the Sauerbrei method (SizePerm, 1999).

USCS Classification: SM - silty sand, SP - poorly graded sand, SW - well graded sand, CL - clay, ML - silt, SC - clayey sand.

Interval is wholly or partially water saturated.

Table 5 *Total Organic Carbon Sample Results*
Maryland Sand, Gravel, & Stone
Elkton, Maryland

Sample ID	Parameter	Method	Units	Reporting Limit	Sample Results
NDA - 09 (5')	TOC	Walkley-Black	mg/kg	110	870
	Percent Soils	160.3	%	10	87.5
NDA - 09 (10')	TOC	Walkley-Black	mg/kg	120	190
	Percent Soils	160.3	%	10	80.1
NDA - 09 (15')	TOC	Walkley-Black	mg/kg	110	3200
	Percent Soils	160.3	%	10	91.9
NDA - 09 (20')	TOC	Walkley-Black	mg/kg	110	6300
	Percent Soils	160.3	%	10	89.4
NDA - 09 (25')	TOC	Walkley-Black	mg/kg	110	420
	Percent Soils	160.3	%	10	92
NDA - 09 (30')	TOC	Walkley-Black	mg/kg	110	170
	Percent Soils	160.3	%	10	88.3
NDA - 10 (5')	TOC	Walkley-Black	mg/kg	110	ND
	Percent Soils	160.3	%	10	81.9
NDA - 10 (10')	TOC	Walkley-Black	mg/kg	110	180
	Percent Soils	160.3	%	10	86.8
NDA - 10 (14')	TOC	Walkley-Black	mg/kg	120	380
	Percent Soils	160.3	%	10	81
NDA - 10 (20')	TOC	Walkley-Black	mg/kg	110	170
	Percent Soils	160.3	%	10	90.8
BWA - 24 (4')	TOC	Walkley-Black	mg/kg	110	780
	Percent Soils	160.3	%	10	88.5
BWA - 24 (8')	TOC	Walkley-Black	mg/kg	110	510
	Percent Soils	160.3	%	10	89.5
BWA - 24 (12')	TOC	Walkley-Black	mg/kg	120	ND
	Percent Soils	160.3	%	10	81
BWA - 24 (16')	TOC	Walkley-Black	mg/kg	140	ND
	Percent Soils	160.3	%	10	73.5
BWA - 24 (24')	TOC	Walkley-Black	mg/kg	120	190
	Percent Soils	160.3	%	10	80.5
BWA - 24 (28')	TOC	Walkley-Black	mg/kg	120	180
	Percent Soils	160.3	%	10	83.7
BWA - 25 (4')	TOC	Walkley-Black	mg/kg	110	770
	Percent Soils	160.3	%	10	89.7
BWA - 25 (8')	TOC	Walkley-Black	mg/kg	110	420
	Percent Soils	160.3	%	10	90.7
BWA - 25 (12')	TOC	Walkley-Black	mg/kg	130	290
	Percent Soils	160.3	%	10	79.7
BWA - 25 (16')	TOC	Walkley-Black	mg/kg	120	180
	Percent Soils	160.3	%	10	84.3
BWA - 25 (20')	TOC	Walkley-Black	mg/kg	130	210
	Percent Soils	160.3	%	10	74.6
BWA - 25 (24')	TOC	Walkley-Black	mg/kg	120	450
	Percent Soils	160.3	%	10	84.2

Sample ID	Parameter	Method	Units	Reporting Limit	Sample Results
PO2 - 20 (4')	TOC	Walkley-Black	mg/kg	110	1000
	Percent Soilds	160.3	%	10	89.4
PO2 - 20 (8')	TOC	Walkley-Black	mg/kg	120	1300
	Percent Soilds	160.3	%	10	83.1
PO2 - 20 (12')	TOC	Walkley-Black	mg/kg	110	1500
	Percent Soilds	160.3	%	10	89.9
PO2 - 20 (16')	TOC	Walkley-Black	mg/kg	120	1900
	Percent Soilds	160.3	%	10	83.5
PO2 - 20 (20')	TOC	Walkley-Black	mg/kg	120	480
	Percent Soilds	160.3	%	10	80.2
PO2 - 21 (4')	TOC	Walkley-Black	mg/kg	110	1000
	Percent Soilds	160.3	%	10	91.3
PO2 - 21 (9')	TOC	Walkley-Black	mg/kg	120	1300
	Percent Soilds	160.3	%	10	83.5
PO2 - 21 (14')	TOC	Walkley-Black	mg/kg	110	1100
	Percent Soilds	160.3	%	10	92.1
PO2 - 21 (18')	TOC	Walkley-Black	mg/kg	120	3500
	Percent Soilds	160.3	%	10	86.3
PO2 - 21 (22')	TOC	Walkley-Black	mg/kg	120	1100
	Percent Soilds	160.3	%	10	82.2
PO2 - 21 (26')	TOC	Walkley-Black	mg/kg	120	440
	Percent Soilds	160.3	%	10	86

Samples collected 13-20 March, 2001

TOC samples from the Pond 02 area were taken from the P02-20 and P02-21 bore locations. Concentrations from this area ranged from 440 mg/kg (0.04%) to 3,500 mg/kg (0.35%) with the highest values occurring from 16-18 feet bgs.

3.4 **AQUIFER TESTING**

On 10 and 11 May 2001, *in-situ* hydraulic conductivity tests were performed on selected Upper Sand monitoring wells. Field methods for conducting the tests are described below.

In-situ hydraulic conductivity tests were performed on the selected upper sand monitoring wells to provide data for assessing the hydraulic conductivity of the aquifer. Prior to conducting the test in each well, the static water level was measured using an electronic water level indicator. The *in-situ* hydraulic conductivity tests were performed by pumping the well at a particular drawdown.

The tests were conducted as follows (Wilson, Cho, Beck and Vardy, 1997). A 0.25-inch inside diameter polyethylene tube was inserted in the well with the tip at an elevation 0.5-foot (15 cm) below the static water level. A Solinst® peristaltic pump was used to pump water from the tube at a rate that produced both water and air. Depending on the flow rate and observed drawdown in the well the tube was then raised or lowered in three inch increments to achieve the correct water and air mixture. The well was then pumped until the flow rate came to equilibrium and the time to collect 200 mL was measured. If the yield was very slow, the yield in five minutes was measured. Specific capacity was calculated in milliliters per second per centimeter of drawdown. The specific capacity was multiplied by an empirical calibration factor, α , to estimate hydraulic conductivity in centimeters per second (cm/sec).

Reduction and analysis of data collected during the hydraulic conductivity tests was performed at the site using the Wilson, Cho, Beck and Vardy (1997) method for unconfined aquifers. The data collected from the tests was used to estimate the hydraulic conductivity for the Upper Sand aquifer at specific well locations. The hydraulic conductivity values calculated from the tests are presented in Table 6.

As shown in Table 6, the single-well hydraulic conductivity tests conducted by ERM in 2001 are in fairly good agreement with the slug tests performed by AEPCO in 1985. The average (geometric mean) hydraulic conductivity of 6.4×10^{-4} cm/sec (1.8 feet/day) also falls within the range

Table 6 - Summary of In-situ Hydraulic Conductivity Tests

Well ID	Hydraulic Conductivity ¹ (cm/sec)	Hydraulic Conductivity ² (cm/sec)
Temporary Monitoring Wells		
<i>Northern Depression Area</i>		
TMW-1	NA	NC
TMW-1S	1.11 E-3	NC
TMW-2	NA	NC
TMW-2S	1.45 E-4	NC
TMW-3	NA	NC
TMW-4	2.02 E-3	NC
<i>Pond 02</i>		
TMW-5	3.45 E-3	NC
TMW-5S	1.72 E-4	NC
<i>Buried Waste Area</i>		
TMW-6	1.52 E-3	NC
TMW-6S	NA	NC
Permanent Monitoring Wells		
<i>Northern Depression Area</i>		
SMW-12	2.76 E-4	4.60 E-4
SMW-13	NA	8.90 E-4
SMW-14	6.11 E-3	2.00 E-3
SMW-15	6.74 E-3	2.90 E-3
SMW-17	2.37 E-4	3.30 E-4
SMW-18A	3.13 E-3	5.50 E-4
SMW-19A	1.49 E-4	3.20 E-4
<i>Pond 02</i>		
SMW-7	1.05 E-4	7.80 E-5
<i>Buried Waste Area</i>		
SMW-2A	4.84 E-5	1.50 E-4
Statistics		
Arithmetic Mean	1.80 E-3	8.53 E-4
Geometric Mean	6.39 E-4	4.90 E-4

¹ - Field estimates of hydraulic conductivity are based on the Wilson et al. (1997) method performed by ERM in May 2001.

² - Field estimates of hydraulic conductivity are based on slug tests performed by AEPCO in 1985.

NA - Not available due to excessive water level drawdown.

NC - Not conducted.

of 10^{-3} cm/sec to 10^{-5} cm/sec that has been published for silty sands (Fetter, 1994; Freeze and Cherry, 1979).

3.5

SUMMARY OF SIGNIFICANT FINDINGS

Supplemental site investigations have generated data necessary for a site-specific technical evaluation of several remedial technologies being considered in the FFS. The new data indicates that:

- There is a very localized area of floating free-phase product (i.e., LNAPL) at NDA, as seen in FLUTe™ testing and in ground water samples. Free-phase product was indicated above and at the static water table on the FLUTe™ liner from boring NDA-11, as well as in bailer samples from shallow well TMW-1S. Analysis of a floating NAPL sample taken from TMW-1S (sample number TMW-1S-RE1; ERM, December 2001), indicated that the combined product sample had a specific gravity close to 1, thus it did not appear to float or sink relative to water. Further, it appears that the various VOC constituents in the mixture are comiscible with respect to each other, and have formed a mixture that has a combined density close to that of water. No evidence of Dense NAPL (DNAPL) was observed in any of the NDA wells sampled during the biodegradation study (ERM, December 2001). The dissolved VOC concentrations in deep wells at the NDA (i.e., TMW-1 and TMW-2) were three to five orders of magnitude less than in the corresponding shallow wells. Although some small globules of apparent DNAPL were noted on the FLUTe™ liner down to the basal clay; these appear to have had a negligible effect on water quality at the base of the Upper Sand.
- Most of the affected soil at NDA is above the static water table;
- There is localized DNAPL present at BWA, as indicated on the FLUTe™ liner at BWA-26 (adjacent to monitoring well TMW-6);
- No NAPL was observed at Pond 02;
- Naturally occurring iron concretions, in some cases as large as a car, are present in site soils. This was predominantly encountered at NDA; and
- Most of the affected media is fine-grained sand and silts. The water permeabilities are generally on the order of 1×10^{-4} cm/sec to 1×10^{-3} cm/sec. This result is consistent with earlier aquifer testing. The permeabilities are generally higher at NDA than at BWA or Pond 02.

4.0 TECHNOLOGY APPLICABILITY ASSESSMENT

4.1 IN-SITU CHEMICAL OXIDATION

Laboratory treatability tests were conducted on soil samples collected from the three principal threat areas of the site. The laboratory tests involved an assessment of chemical oxidation efficiency using two oxidants, potassium permanganate and sodium persulfate. The tests were run separately, concurrently, and sequentially to evaluate the effectiveness of the different scenarios on site-specific soil. A treatability study report is presented in Appendix C. Additional test results from an extended test period are presented in Appendix D.

4.1.1 *Factors Affecting Applicability*

The first factor affecting the applicability of *in-situ* chemical oxidation is the reactivity of the selected oxidants with the contaminants of concern (COCs). The selected oxidants must react chemically with the COCs to produce less toxic reaction products.

A second key factor in determining the applicability of chemical oxidation is the reactivity of the oxidants with materials in the matrix other than the COCs. The presence of other oxidizable materials, such as other organic compounds or reduced iron, increases the matrix demand for the oxidant without reduction of the COCs. A high matrix demand can, therefore, make chemical oxidation economically impractical.

The effectiveness of chemical oxidation is dependent on contact between the oxidant and the contaminant. This in turn is dependent on the uniformity of oxidant delivery. There are a number of delivery techniques, which can be used to apply chemical oxidants. These will have varying degrees of mixing and distribution uniformity. Injection wells screened over a wide horizon will be the most non-uniform. The distribution will follow the permeability. Using injection wells with narrow screen horizons increases the distribution and can minimize preferential flow. Combining injection and fracturing or mechanical mixing provides the best mixing and distribution. Generally the more permeable the soil and the more uniform the lithology the easier it is to distribute the oxidant and the greater the effectiveness of the less aggressive techniques.

In the vadose zone, the amount of oxidant available will be limited due to the draining of the oxidant solution from the soil matrix. Vadose zone soils will only retain about 20-30% of the volume of solution (field saturation) injected. Thus the oxidant available will be 1/3 to 1/5 of the amount injected. Based on this, application of an oxidant solution will be able to treat 3 to 5 times more contaminant in the saturated zone than in the vadose zone.

The reactions between the contaminants and the oxidants are not instantaneous. The contact time issues may be further exacerbated by the sorption of contaminants to the soil matrix. If the contaminants are strongly held either because of a high partitioning coefficient or because of low permeability, the time required to treat the contaminant will be increased. Most of the reactions occur in the aqueous phase. The total treatment time is therefore the sum of the time to desorb the contaminant and the reaction time. Some of the contaminants can require several weeks to react, particularly when in the presence of other more amenable contaminants. Thus, it is important to maintain oxidant contact with the affected soil. Several factors need to be considered, therefore, in applying *in-situ* chemical oxidation. These include the amount of recharge and the rate of ground water flow. A high degree of recharge or a rapid ground water flow rate may limit the effectiveness of chemical oxidation by flushing the oxidant from the matrix.

The application of oxidants may increase the solubility of metals. The main factor appears to be a pH shift to acidic conditions. This can be mitigated by buffering or pH adjustment. Some soluble metals such as iron are converted to insoluble particulate species.

4.1.2 *Effectiveness Evaluation*

A laboratory study was conducted to assess the effectiveness of two oxidants, potassium permanganate and sodium persulfate, applied separately and in combination, at reducing the concentrations of the COCs at the site. The results of the laboratory treatability study are presented in Appendix C. Key results are discussed below.

There do not appear to be any truly recalcitrant contaminants present among the COCs with respect to permanganate or persulfate oxidation. Reductions in contaminant mass, versus the final control sample, were observed for each of the COCs in one or more of the oxidant tests. All the COCs appear to react; however, some react slowly.

None of the 38-day tests reduced soil concentrations for all the COCs to below the principal threat criteria for protection of ground water at the

site. However, this may be a result of the time limitations on the tests. Methylene chloride; chlorobenzene, 1,1,1-trichloroethane (1,1,1-TCA); and (1,2-Dichloroethane) DCA appear to be the slowest to react. To effectively treat the COCs may require several applications.

The reactivity of the two oxidants (persulfate and permanganate) and their reaction pathways are different for different COCs. Using the two oxidants appears to give better performance than either oxidant by itself. Using a blend of permanganate and persulfate would be the most cost-effective approach, but the results did not indicate this approach to be effective at reducing chlorobenzene, 1,1,1-TCA or acetone. There was better performance using the oxidants in sequence. However this may increase the costs if mixing is required for delivery of the oxidants.

The 38-day test period was also extended to 70 days. The results of the extended testing were summarized in a letter report dated 04 September 2001. A copy of that report is presented in Appendix D. An extended contact-time bench test (i.e., 70 days) was conducted to determine whether chemical oxidation with permanganate or persulfate could be effective in reaching the principal threat criteria for all of the COCs. Additional samples from the same initial batch startup for the 38-day tests (i.e., T=0) were allowed to react with the tested oxidants for an additional 32 days, thus resulting in a 70-day test period. The test cells and procedures were identical to those used in the 38-day tests. The tested samples were allowed to react at room temperature for a total of 70 days, in order to compare the results with those previously reported in the base study using a reaction time of 38 days. This extended duration testing provides useful data in determining the contact time that would be necessary to achieve these reductions.

The trends in the Day 70 data are similar to those observed with the Day 38 samples (Appendix D). In general, permanganate was highly effective in removing the chloroethenes, toluene, ethylbenzene, xylenes, and 4-methyl-2-pentanone (MIBK), but had only limited effect on methylene chloride, benzene, chlorobenzene, and the chloroethanes. The persulfate appeared to be significantly more effective in removing chloroethane, chlorobenzene, and benzene; significantly less effective on tetrachloroethene, ethylbenzene, and xylenes; and also had limited effectiveness on methylene chloride, 1,2-dichloroethane, and 1,1,1-trichloroethane. Combining the two oxidants (concurrently or sequentially) seemed generally to have additive but not synergistic effects, with the possible exception of effectiveness in removing 1,1,1-trichloroethane. Some improvements in the removal of methylene chloride, chloroethane, and chlorobenzene were observed with the extended duration; but, in general, the extended duration did not significantly increase removal effectiveness.

4.1.3 *Cost Factors*

The oxidant demand was observed to be very high in the NDA soil samples, but within a reasonable range in the samples from the Pond 2 and BWA soil samples. The very high oxidant demand in the NDA may make *in-situ* chemical oxidation of this material economically impractical.

The potential need for sequential oxidant treatment and the long contact time that would be required to reduce the COC levels to the principal threat criteria may necessitate multiple applications of the oxidants, particularly in the vadose zone. This may make *in-situ* chemical oxidation economically unattractive if soil mixing is required for each application. Therefore, cost-effective application of chemical oxidation may be most applicable to the saturated zone, where the oxidant would remain in contact with the affected soil for an extended duration.

Overall, based on the results of the treatability screening tests it appears that the cost of utilizing chemical oxidation as the primary treatment of all three principal threat source areas would be significantly higher than estimated in the draft FFS.

4.1.4 *Implementability*

Based on the high oxidant demand and long contact time requirements indicated in the results of the bench-scale testing, it appears that cost-effective implementability of chemical oxidation may be limited to the saturated zone as a component of a remedy. Chemical oxidation is enhanced by elevated temperatures. If additional testing of thermally enhanced oxidation proves effective, the application of oxidants could be incorporated with application of an *in-situ* thermal technology to reduce the cost of thermal treatment.

4.1.5 *Data Needs for Further Evaluation*

Testing of the use of oxidants in conjunction with heating may be advisable during further evaluation of *in-situ* thermal treatment. This work could be incorporated into the remedial design phase. Recent development work using distilled water spiked with various VOCs has shown that persulfate at elevated reaction temperatures (45° C to 55° C) can accomplish essentially complete destruction of all of the CoCs at the MSG&S site over a 5 to 20 day reaction period. A description of this preliminary process development testing and results is provided in Appendix D.

The preliminary results from the testing of persulfate oxidation at elevated temperatures could have a significant implication for the potential combined use of *in-situ* thermal and *in-situ* chemical oxidation at the MSG&S site. The introduction of sodium persulfate during *in-situ* heating may also decrease the time and temperature of heating required to remove constituents from both the soils and ground water by combining the effects of thermal stripping with thermally activated chemical oxidation, potentially resulting in significant reductions in both remediation time and energy use. Heated persulfate experiments using soil alone or soil slurries have not been completed. However, based on the results of testing with water alone, it is possible that higher reaction temperatures may result in significantly greater VOC destruction efficiencies in the presence of soils than were achieved in the MSG&S bench-scale testing that was conducted at room temperature. Additional testing would be required to establish the baseline conditions for this approach.

Because of the high matrix oxidant demand observed in some of the oxidation bench tests, it may be appropriate to evaluate the use of hydrogen peroxide to reduce the background oxidant demand. Hydrogen peroxide could be injected in low concentration at high volume to reduce the oxidant demand prior to the introduction of other oxidants. Additionally, due to the presence of iron oxides at the site, gratuitous Fenton oxidation of the target compounds may result.

4.2 *IN-SITU THERMAL TREATMENT*

There are several *in-situ* thermal remediation technologies that may be applicable for this site. The additional investigative activities were conducted to assess the viability of *in-situ* thermal remediation, and to a lesser extent help determine which of the technologies would be most applicable. In addition, ERM contacted respected vendors of the technologies for their input in assessing the applicability of their specialty technology to the MSG&S site:

In-situ Electrical Resistive Heating (SPH)

- Thermal Remediation Services, Inc.
- Current Environmental Solutions, Inc.

In-situ Steam Treatment

- SteamTech Environmental Services

The technologies that may require further assessment if *in-situ* thermal treatment is retained in the FFS, are electrical resistive heating (SPH, three-phase heating, joule heating, steam treatment, or RF heating). The most likely applicable *in-situ* thermal technologies are SPH and steam treatment, based on an initial screening, and these are briefly evaluated below.

Electrical Resistive Heating

In this *in-situ* treatment technology, direct electrical current is passed through the soil. The resistance to the current flow causes the soil to heat. There are two primary electrical resistance-heating technologies – joule heating and six-phase heating. Joule heating uses parallel arrays of anodes and cathodes. Spacing is typically 8-10'. Typically 60 Hz power is used. Six-Phase Heating (SPH) uses a hexagonal array of electrodes typically placed 20-30' across the array. Three phase power is used and each phase is split into a "+" and "-" phase. Electrical resistance heating is used to heat the soil to approximately 100°C. It generally requires a moderate water content to enable current to flow between electrodes.

Compounds that are present as a separate phase (i.e., NAPL) with boiling points below 100°C are volatilized; those with boiling points above 100°C are removed via steam distillation that is generated through the boiling of ground water and residual moisture content in the unsaturated zone. If free-phase NAPL is present, steam distillation will take place. When the vapor pressure of the NAPL and ground water equals the vapor pressure of the atmosphere, boiling of the NAPL will take place, often at temperatures below the actual boiling point of individual VOCs. Electrical resistance heating is typically effective in low permeability soils. It is best applied to small to moderate size sites, sites with a moderate to high water content, and contaminants with a moderate to high vapor pressure.

Steam Treatment

Steam is an aggressive heating method. Steam has a fairly high thermal capacity and can be used to heat the subsurface if it can be effectively applied. Steam is generally injected into the more permeable horizons at or below the zone that needs to be treated. The process results in the volatilization of the contaminants of concern, which are subsequently recovered through one or more vapor extraction wells. Initially, steam will condense in the soil during the heating process resulting in the production of contaminated water. The volume of water typically decreases as the treatment area heats to the target temperature. On site steam generation can be moderately costly relative to sites where plant

steam is available. Steam is not available at MSG&S. Steam heating has been successfully applied to large sites, including several federal facilities. Steam is used for sites with moderate to high soil and aquifer permeabilities, sites with high water saturation, and sites with moderate to high contaminant levels. Treatment with steam is often called dynamic underground stripping (DUS). The technology application is often combined with a back-end process known as hydrous pyrolysis oxidation, or HPO. HPO is a process by which physical/chemical destruction of the organic compounds takes place under the presence of heat and oxygen. After the subsurface is heated by steam, the remaining organic material is thermodynamically unstable at the elevated temperatures and can be oxidized/destroyed in the presence of air.

For this evaluation SPH and steam treatment were evaluated for applicability for the MSG&S site. Future evaluation, if necessary, may include a detailed evaluation of other *in-situ* heating technologies, including joule heating, 3-phase heating, and RF heating. In a general sense, these *in-situ* thermal technologies have similar technical advantages and disadvantages relative to one another. All of these technologies heat the soil to generate steam and VOC-laden vapors. Ground water, NAPL and vapors are recovered at the ground surface beneath an impervious cover, or via extraction wells.

4.2.1 *Factors Affecting Applicability*

Site-specific conditions can affect the applicability of electrical resistive (SPH) or steam heating as a feasible and implementable remediation technology. For the principal threat OU3 soils at the MSG&S site, lithologic and hydrogeologic conditions present the most substantial evaluation criteria. The nature and concentrations of the contaminants of concern, all VOCs, make SPH or steam viable technologies. Factors that would affect the design of the remedial system incorporating these technologies at the MSGS site include soil heterogeneity, high constituent concentrations in localized areas, and the localized presence of free-phase liquid or adsorbed, residual product. Potentially viable soil heating technologies include the longer-term fixed heating systems such as SPH or steam where higher temperatures over a prolonged duration result in an increase in VOC removal efficiencies. SPH and steam treatment have been utilized with high concentrations of contaminants in both the unsaturated and saturated zones at other sites. Higher soil moisture contents typically result in slightly higher costs.

At MSG&S, the site lithology, hydrogeologic characteristics, and nature of the contamination appear to be suitable for remediation of using SPH or steam technology. Many of the constituents of concern have boiling

points greater than 100°C, and thus the subsurface heating would result in the steam stripping of the VOCs, with vapor/steam extraction taking place at the surface or dedicated extraction wells. Applications of the technology at other sites has shown that degradation of free-phase and dissolved-phase chlorinated and non-chlorinated VOCs can also take place at elevated temperatures but below 100°C, most likely due to either volatilization of free-phase product in the presence of water, or oxidation under unstable thermodynamic conditions. The variable and relatively low permeability of the soils at MSG&S is not a concern for soil heating (and volatilization), except in the context of vapor recovery. In order to ensure that the steam and organic vapors are recovered, an engineered cap will likely be needed to be placed above any steam/vapor extraction ports at the ground surface.

Some water will be generated from the application of SPH or steam treatment, predominantly from initial water extraction and subsequent steam condensate as the treatment area temperature increases. The steam condensate is expected to be relatively free of VOCs after it is processed through a heat exchanger. The water will require storage in onsite tanks pending some level of treatment (e.g., carbon) before discharge. The vapor phase will either be captured at the ground surface, most likely through an integrated set of horizontal piping set beneath an impermeable cover (i.e., geotextile membrane liner), or through a series of vertical extraction wells. VOCs would be removed from the vapor phase through the use of catalytic oxidation or regenerative carbon.

The steam or SPH technologies would require separate implementation in each of the three principal threat areas of the site. The technologies can be applied concurrently, or sequentially. In addition, it may be appropriate to consider a combination of steam treatment and SPH application, depending on the individual characteristics of the separate principal threat areas. Due to the relatively long time it takes to heat an area to the target temperatures, performing the technology application concurrently would significantly reduce the implementation time. Conversely, concurrent application for SPH would require significant electrical demand, the feasibility of which would require further evaluation. Concurrent application of steam treatment is more realistic since an average-size portable steam generator would provide ample steam to treat the three principal threat areas concurrently.

The most notable factor affecting the applicability of steam treatment for the principal threat areas at MSG&S is the local subsurface permeability, and in particular, the ability of steam to be injected at pressures that do not result in fracturing. If steam delivery can not take place, or can not be controlled, the technology is generally not effective. If steam injection

under pressure results in fracturing, this would cause the generation of uncontrollable preferential steam-flow pathways, non-uniform heating, and possibly uncontrollable vapor recovery.

Steam transmission through the subsurface also is best applied where the stratigraphy is fairly uniform, although steam remediation has been successfully applied to sites with heterogeneous soils where the hydraulic flow system is understood. In uniform stratigraphy, steam can be injected into, and recovered from, the more permeable horizons (i.e., sand layers). Less permeable horizons (i.e., silts and clays) are heated inductively through contact with the heated steam zones. If the stratigraphy is not uniform, steam injection, steam recovery and temperature monitoring may prove difficult to control.

Steam treatment is an effective technology for VOC removal under saturated and unsaturated conditions, predominantly in more permeable media. If subsurface conditions allow for effective steam injection and recovery, the technology can be very effective in organic compound removal. Conversely, SPH treatment is generally applied at sites with lower permeabilities.

In addition to hydrogeologic condition, steam treatment and SPH treatment require the capture and treatment of steam and organic vapors, monitoring of subsurface temperatures to assess the distribution of heat throughout the three-dimensional treatment area, and a steam or electrical source. Monitoring and steam generations are factors that will not influence the applicability of the technology, but do influence the implementation, timeframe, and costs associated with technology application.

4.2.2 Effectiveness Evaluation

It appears that application of SPH or steam treatment can achieve the principal threat criteria established for the project, although there are not many case studies to indicate remedial endpoints. The soils can be heated for a period of time at which monitoring data confirms the levels of COCs have been reduced to concentrations below the principal threat criteria. Inasmuch as all of the constituents of concern are VOCs, the organic compound mass in the principal threat areas will either be removed by volatilization, steam removal, or by oxidation.

If geologic conditions are suitable for uniform steam transmission or electrically generated heat transmission, this technology can be very effective as a remedial alternative for VOC contamination in unsaturated and saturated media. Clean up goals can likely be met as the treatment area achieves the necessary temperatures over time.

As noted above, for steam treatment, the steam delivery is the key component to generating uniform heating and controllable steam/vapor recovery. At the principal threat areas at MSG&S, the stratigraphy has not been found to be uniform, in large measure due to the presence of fill material in these areas. Furthermore, the permeability of the soil and unconsolidated sediments in some areas to be remediated are reflective of fine sands, and silts, with hydraulic conductivities on the order of 1×10^{-5} cm/sec to 1×10^{-4} cm/sec. In consultation with SteamTech Environmental Services, a respected vender of steam technology, these permeabilities are on the edge of what would likely be deemed applicable for technology application. Essentially, steam injection under some pressure could result in fracturing of the soil, non-uniform distribution of steam and, possibly the generation of uncontrollable steam or vapor vents at the ground surface. In addition, lower permeable soils equate to lower injection pressures and a lower radius of influence around each steam injector, thus requiring a greater number of injection and recovery points. Areas of the site with hydraulic conductivities in this range may be more amenable to thermal treatment by other means (i.e., electrical resistive heating) when factors such as treatment depth and effective radius of influence are considered. Pre-design studies would be warranted should *in-situ* thermal remediation be considered further.

4.2.3 Cost Factors

The most significant cost factor associated with SPH or steam treatment is the time of treatment, which will largely depend on the target remedial goals to be established. The time component of the remediation has a direct affect on the single most costly component of the SPH technology, electricity, and to a slightly lesser extent for steam, which requires a fuel source on site. Approximately one third of the total costs for SPH application will be energy demand, slightly less for steam. The remaining costs include capital equipment, labor costs for system installation, system operation and maintenance, and monitoring, vapor and water phase treatment costs, and analytical costs.

Steam application could likely be conducted on all three principal threat areas concurrently. A steam generator would have to be placed centrally between the three areas to convey the steam to the injectors around the principal threat areas. Concurrent application would shorten the project timeframe for heating, relative to other thermal treatment options (e.g., SPH, LTDD) that would most likely need to take place sequentially for the three principal threat areas of the site due to equipment and electrical power constraints. Steam and SPH could be applied concurrently at different areas of the site, if that is deemed applicable in subsequent evaluation and design stages of the project. In that scenario, costs could be minimized by using a centralized system for vapor and water-phase

treatment. Shortening the timeframe to heat the three areas would result in some cost savings for oversight, operation & maintenance (O&M), and monitoring.

4.2.4 Implementability

SPH and steam treatment can be implemented at the three principal threat areas of the MSG&S site. The lower permeabilities of the soil, particularly at BWA and Pond 02, may reduce the cost effectiveness of steam treatment at those locations. This would require additional assessment. The site lithology, nature of contamination, and the volume of principal-threat area treatment appear to be viable for remediation by *in-situ* thermal treatment.

Due to the boiling points of some of the constituents of concern, it will be necessary to heat the ground for a period of time to temperatures in excess of 100°C, thus boiling the ground water. As noted above, the length of time for SPH treatment or steam treatment will be directly related to treatment goals. On that note, it may be possible to aggressively treat the site for a period of time at temperatures above water boiling (i.e., high energy demand), and then continue residual treatment at temperatures below 100°C (i.e., considerably lower energy demand) for additional degradation under unstable thermodynamic conditions (e.g., HPO). The period of time for steam injection time could be reduced if HPO is applied. Overall, however, the remediation timeframe would increase with this approach, but at a reduced energy cost. Pre-design studies would be warranted should *in-situ* thermal remediation be considered further.

The principal advantages of *in-situ* thermal treatment (electrical resistive heating or steam treatment) is that it can be implemented at this site with minimal site disturbance relative to *ex-situ* treatment, and can achieve the remedial project goals. The actual remedial goals will affect the project costs and timeframe, but not the applicability of the technology. Another advantage is that vapor and steam recovery will be at the ground surface under an impervious geotextile or asphalt plenum, or through dedicated vapor recovery wells, thus facilitating an effective means for soil vapor extraction and minimization of fugitive emissions. The technology can be applied to affected media above and below the water table.

The principal disadvantage of electrical resistive heating or steam treatment at the MSG&S site is largely logistical and cost-related. For SPH, the electrical and equipment demands will likely require the sequential application (rather than concurrent application) of SPH to each principal threat area, thus extending the treatment time and associated project costs. Treatment below the water table does not significantly add

to project costs using either technology, although treatment below the water table will result in greater steam generation and associated water treatment costs.

According to several vendors of the SPH technology, Thermal Remediation Services [TRS] and Current Environmental Solutions [CES]), the presence of free-phase product will not appreciably affect the applicability of the technology. A similar response was received from the vendor of steam treatment technology, SteamTech. It should be noted that the boiling point temperatures of two of the constituents of concern at MSG&S, chlorobenzene and tetrachloroethene (PCE), are 132°C and 121°C, respectively. However, it is interesting to note that removal of this product by "boiling" would actually take place at sustained temperatures below 100°C. Further testing and evaluation would be required to assess whether it would be more prudent (and cost-effective) to attempt to remove the free-phase (floating) product prior to any application of SPH or steam treatment.

The application of SPH or steam treatment would result in significant heat retention in the treatment areas, in all likelihood for a period up to a year after the application is completed. This will have an effect on the microbiology, the extent to which is unknown. At some sites (i.e., the Gas Pad Site at the Lawrence Livermore Laboratory), the application of a thermal remedy has been shown to have a positive effect on microbial activity with respect to biodegradation of hydrocarbons. Additional research testing has been recommended at selected test sites in an attempt to further quantify the effect of heat on the resident microbial populations in the treatment areas. SPH treatment would result in residual anaerobic conditions; steam treatment would result in residual aerobic conditions.

4.2.5 Data Needs for Further Evaluation

Some additional laboratory testing was recommended by one vendor (CES) to optimize full-scale design parameters. For steam treatment, pilot testing would quantify the effective radius of influence to inject and recover steam at pressures that would not result in fractures and uncontrollable preferential flow pathways. All the vendors recommended that some modeling activities would need to be performed to optimize system design, and predict the timeframe for effective remediation.

4.3 EX-SITU LOW-TEMPERATURE THERMAL DESORPTION

One of the remedial technologies that is being considered for the MSG&S site is low temperature thermal desorption (LTTD). LTTD is an *ex-situ* remediation process in which excavated soils are screened, mixed and

exposed to elevated temperatures below those at which combustion will occur. LTTD can be used on site with a mobile unit, or at fixed locations off-site. Volatile constituents are driven from the soil into a concentrated gas stream that then requires treatment prior to release to the atmosphere. Techniques for treating the constituent-laden gas stream produced by LTTD include condensation of solvents, gas-phase carbon adsorption or thermal oxidation. The treated soils are typically returned to the excavated area. This technology requires careful monitoring of the soil feed rate and operating temperatures to achieve cleanup levels for the constituents at the site, which is dependent on the temperature, retention time within the desorption unit, and degree of mixing and heat transfer. Soils with VOC concentrations in the tens of thousands of mg/kg have been treated to levels below 100 mg/kg using this technology. Residuals (e.g., condensates and spent activated carbon) from this treatment technology will require further treatment.

Based on the nature of the contaminants, the measured concentrations, and the soil characteristics, and based on an evaluation provided by Maxymillian Technologies, only indirect-fired LTTD was considered in the evaluation. Indirect-fired LTTD merely means that the source of the heat (i.e., flames) is not in direct contact with the soil. In addition, due to the estimated volume of material that may require treatment, only an on-site treatment options was considered.

After excavation, the soil is sieved to remove large material (i.e., roots, rocks, and iron-concretions), as well as residual water for soils excavated below the water table. Typically, indirect-fired LTTD units do not work well for soil with moisture contents in excess of about 18 percent. The soil is then fed through a heating chamber on a conveyor. Typical feed rates are 10 to 14 tons per hours, depending on soil type, and contaminant type and concentrations. Organic compounds are volatilized and subsequently treated (typically, through catalytic oxidation or regenerative carbon). The treated soil can be returned to the excavation.

4.3.1 *Factors Affecting Applicability*

As an on-site, *ex-situ* remediation technology, the factors that control the applicability and feasibility of the technology at this site are significantly different than the *in-situ* thermal and oxidative technologies. These factors include logistical constraints such as excavation, dewatering and fugitive emission controls. It also includes implementation issues such as soil screening to remove large material (i.e., roots, rocks, and naturally-occurring iron-concretions), soil staging to reduce moisture content for soil removed beneath the water table prior to LTTD, and ground water treatment and discharge.

Based on the field data, geotechnical data, and chemical data collected from the three principal threat areas of the site, LTDD can be an effective remedial technology to treat the OU3 soils. The technology can be used to remove VOC mass from affected soil; soil from both above and below the water table. For saturated soil that is excavated, the soil will require dewatering and blending with dry soil in order to reduce moisture content for effective treatment. Although the geotechnical testing concluded that the site soils have a low plasticity, the presence of clay lenses in the excavated soil may require longer retention time in the thermal heating chamber of the LTDD unit. If this is the case, it will lengthen the treatment time and effect remediation costs.

In addition, after the soil is treated, it will likely be replaced into the excavation in each principal threat area. Hence, the technology requires that affected ground water be removed and treated such that the treated soil does not become impacted again on return to the excavation. This presents some application concern, since a dewatering action to facilitate excavation beneath the water table may not remove all the affected ground water around the principal threat area excavation. Affected ground water around or beneath the excavation areas that is not removed for treatment will potentially flow back into the excavation area subsequent to the termination of dewatering actions. In this remediation alternative, treatment of OU3 soils becomes an *ex-situ* treatment of both soil and ground water.

In addition, implementation of LTDD treatment will potentially require that a portable enclosure be placed over the excavation to control fugitive VOC emissions. As a result air within the portable structure will need to be treated, and may present implementation constraints due to worker exposure from organic vapors from the affected soil, and carbon monoxide from heavy equipment operations inside the structure.

4.3.2 *Effectiveness Evaluation*

Maxymillian indicated that LTDD could achieve either the principal threat or the SSL goals established for the project. Previous case studies indicate that achieving the SSL levels may require significant re-processing of material. The feed rate for soil treatment can be monitored and controlled to ensure sufficient residence time in the indirect heat chamber of the LTDD unit. Indirect-fired LTDD has been used to successfully remediate soils affected with polychlorinated biphenyls (PCBs), and hence application of this technology will be able to reduce VOC concentrations in soil to levels significantly below the principal threat criteria.

4.3.3

Cost Factors

On-site *ex-situ* LTTD presents some significant cost factors that are not significant with the *in-situ* technologies. Most notably, application of this technology requires costs associated with dewatering and ground water treatment and discharge, set-up of a portable structure that will require reassembly in each treatment area, and health and safety costs associated with worker exposures inside the portable treatment building. The amount of water requiring treatment and discharge will be significantly greater than the steam condensate treatment that would take place under the *in-situ* thermal treatment scenarios. This is due to the need to control, capture, and treat the ground water that flows into the excavation from outside of the principal threat areas during dewatering operations.

In addition, an onsite alternative fuel source will be required for operation of the LTTD unit; probably propane or diesel fuels. Due to the need for excavation, dewatering, soil sieving and drying to remove large material and residual moisture, health & safety constraints, soil backfilling, and equipment remobilization, LTTD will likely take substantially longer to implement than *in-situ* thermal treatment. This will have an impact on project costs (e.g., O&M costs, longer monitoring period for fugitive emissions), project oversight).

4.3.4

Implementability

Although the technology does present some significant logistical constraints (e.g., dewatering, water treatment, vapor controls, worker safety), it can be implemented at the MSG&S site. The principal advantages of LTTD application are the complete and effective treatment of the affected soil that is fed through the LTTD unit. Treatment goals for the excavated soil can be met. If significant clay lenses are encountered during excavation, the LTTD thermal treatment may require that the feed rate be reduced, or that the soil be sieved or crushed, to ensure adequate heating. Geotechnical testing of the principal threat area soils found the clays to a low plasticity (i.e., low cohesiveness), so this should not be a factor with respect to treatment efficiency.

The principal disadvantages of the technology application at MSG&S are logistics, timeframe, health and safety concerns, and cost. As an *ex-situ* technology, constraints arising from excavation, dewatering, sieving to remove large concretions and roots, drying to reduce residual moisture content of soils from beneath the water table, water treatment and discharge, and working in an sealed enclosure, will all need to be addressed during design and implementation. Possibly the most significant issue to be addressed, will be health and safety limitations placed on workers in the portable temporary enclosure due to vapors

from the soil, and fumes from heavy equipment operating within the enclosures. Engineering solutions to ensure sufficient airflow would need to be derived during the design phase. Water treatment is also a significant logistical issue since substantially more water will be generated (and require treatment) than corresponding *in-situ* thermal treatment alternatives, due to the need to dewater the principal threat areas to facilitate excavation of affected soil beneath the water table.

As noted above, the implementability of the LTDD technology is, in part, based on the treatment objectives. To reiterate, affected ground water not removed during dewatering will subsequently contact the treated soils that are placed back into the excavation.

4.3.5 *Data Needs for Further Evaluation*

With the exception of delineation of excavation areas, this remedial technology will not require significantly more data collection to facilitate design.

The supplemental investigation provided new information on the presence of NAPL and the vertical distribution of contaminant mass in each principal threat area. The innovative technologies known as FLUTe™ Ribbon NAPL sampler and Membrane Interface Probe System (MIPs) were shown to be useful in the vertical characterization of the principal threat areas. These technologies can be very useful in delineating the principal threat material during the remedial design phase.

At NDA, the depth to clay was found to be deeper than indicated in previous borings. This could increase the volume of material in the Upper Sand requiring treatment. However, the majority of VOC mass appears to be at or above the water table. The FLUTe™ investigation indicated the presence of discernable intervals of NAPL at or above the water table, which could account for a substantial percentage of the mass of contaminants in the NDA area. Installation of two shallow and deep well pairs in the area confirmed the presence of a localized light NAPL at the NDA. The FLUTe™ results indicated only isolated spotting of NAPL below the water table. The deep well ground water results showed that ground water concentrations at the bottom of the Upper Sand are relatively clean, with no indication of impact from the presence of DNAPL (ERM, December 2001). Similarly, the supplemental investigation data from the BWA and Pond 02 indicate that the bulk of the contaminant mass appears to be located at or above the water table. At BWA, NAPL was indicated on the FLUTe™ liner at the ground water interface, and as small spots below the water table. At Pond 02, the results of the FLUTe™ testing did not indicate the presence of any NAPL to the basal clay. One shallow and deep well pair was installed in both the BWA and at Pond 02. In both these well pairs, the deep well results were substantially lower than the results from the corresponding shallow well (ERM, December 2001). No NAPL was observed in either of the deep wells (TMW-5 and TMW-6). However, some VOC concentrations reported in Upper Sand wells downgradient of the BWAⁱ (Phase I/Phase II Quarterly Ground Water Monitoring Reports prepared by Baker Environmental, Inc.) may be suggestive of some DNAPL impacts in this area of the Site.

ⁱ Buried drums were removed from this area in 1990 as part of the OU1 remedy.

In-situ thermal treatment is a remediation technology that has been known and tested at other sites for over a decade. Although there have been numerous pilot-scale applications, few large sites have been documented to have undergone full-scale *in-situ* thermal remediation. Similarly, the literature base is limited for large sites that have undergone full-scale remediation using *in-situ* chemical oxidation with potassium permanganate or sodium persulfate. In general, the number of documented successful applications of either of these innovative and promising technologies, for sites similar in scope and size to MSG&S, is limited, particularly relative to more conventional treatment technologies (e.g., *ex-situ* LTDD, pump-&-treat, soil vapor extraction, containment, etc.).

The supplemental investigations conducted for the remedial alternative evaluation yielded some results that appear to limit the potential effectiveness of *in-situ* chemical oxidation as a preferred remediation technology for consideration in the FFS. *In-situ* chemical oxidation may be viable in the context of supplementing a thermal technology, particularly under saturated conditions (i.e., below the water table). However, both *in-situ* thermal treatment and *ex-situ* thermal treatment appear to be potentially applicable technologies for the OU3 principal threat area soils at MSG&S.

Testing of the oxidation efficiency of potassium permanganate and sodium persulfate, independently, concurrently, and sequentially, yielded mixed results. In general, some constituent concentrations decreased significantly under one or more oxidation scenarios. Laboratory treatability studies for *in-situ* chemical oxidation testing indicated that there is generally a high natural chemical oxidant demand in site soil, particularly at NDA. More significantly, some VOCs, particularly chlorobenzene, did not appear to be adequately oxidized by either potassium permanganate or sodium persulfate during bench-scale tests. In the saturated zone, unused oxidant would remain available for VOC oxidation as ground water flows through the treatment area. In contrast, residual oxidant in the unsaturated zone would not be as mobile and amenable for contaminant oxidation except when it is mobilized during periods of precipitation and subsequent infiltration. As a result, potential applicability of permanganate or persulfate oxidation would appear to be more favorable for the saturated zone, where longer oxidant contact time can be sustained. In addition, CES (one of the vendors of SPH) suggested that we consider and further evaluate the application of *in-situ* chemical oxidation in combination with *in-situ* thermal treatment. This is further supported by the preliminary results of thermally enhanced chemical oxidation using sodium persulfate (Appendix D).

With respect to *in-situ* thermal treatment, additional boring logs, geophysical logs (i.e., MIPs resistivity logs), and aquifer testing provided

data on the heterogeneity and permeability of the treatment area soils. To assist in the data evaluation, ERM contacted several respected vendors of *in-situ* thermal treatment for their input in evaluating the applicability of the technology which they market to this site. The relatively low aqueous permeabilities at Pond 02 and BWA may not be conducive to steam injection and recovery, according to one of the principal vendors of steam technology (SteamTech). In their assessment, electrical resistive heating (i.e., SPH) may be a more cost-effective technology at these principal threat areas. For steam application, low-permeable strata will require a larger number of steam injection and steam recovery wells due to the reduced effective radius of influence. Consequently, this will have a significant effect on the project costs. Applicability of steam treatment, particularly at Pond 02 and BWA, would require further evaluation in the treatment system design phase.

SPH and steam treatment, or a combination of the two, appear to be viable treatment technologies to meet the principal threat criteria at the site, based on the input from the various vendors. However, for these innovative technologies, there is a lack of examples where these or more stringent cleanup criteria have been achieved. Further technical, logistical and cost evaluation is recommended for a determination as to whether steam treatment, SPH, RF heating, or joule heating would be the preferred *in-situ* thermal treatment technology.

The supplemental investigation data also suggests that *ex-situ* thermal treatment by LTTD is technically feasible for the site, and can achieve the principal threat criteria. Application of this technology will incur some logistical constraints due to soil excavation, excavation dewatering, and control of fugitive emissions. For the successful applications that have been completed to date, many have been conducted with higher constituent cleanup goals than the Soil Screening Levels (SSLs) that have been derived for the MSG&S site. In several cases using LTTD, the literature indicates difficulty in achieving levels similar to the calculated SSL values. Under this treatment scenario, the metals data obtained from TCLP testing indicates that Land Disposal Restrictions for metals will not be an issue because the waste materials (i.e., affected soil) in the principal threat areas are not characteristically hazardous.

Baker Environmental, Inc. 2001. Phase I/Phase II Quarterly Groundwater Monitoring Report, Maryland Sand Gravel and Stone Site, Elkton, Maryland, 2001.

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Appendices

Appendices

A

Appendix A
Soil Boring Logs

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-08 / TMW-1 / TMW-1S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/14/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 44 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
0	1	2.0	82.3		Fine SAND, light brown (5 YR 5/6), strong odor, dry.	Soil color based on Munsell charts. USCS grain size classification.
2						
4	2	2.5	>2000		Fine SAND, light brown, occasional pebbles, strong odor, dry.	
6						
8	3	1.5	>2000		At 7 feet, Silty SAND, grayish orange (10 YR 7/4), trace Clay. As above, wood fragments, grades to light brown, strong odor, moist.	
10						
12	4	3.0	>2000		Fine SAND, moderate brown (5 YR 3/4 to 4/4), little Silt, occasional coarse Gravel, strong odor, wet.	
14						
16	5	0.9	>2000		As above, pushed Gravel from 16 feet to 18 feet.	
18	6	2.0	>2000		As above with iron concretions to 18.5 feet. At 18.5 feet, medium SAND, dark yellowish orange (10 YR 6/6), trace coarse Sand, moderate orange pink (5 YR 8/4), strong odor, wet.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-08 / TMW-1 / TMW-1S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/14/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 44 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS	
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample			
20	6	2.0	>2000		At 18.5 feet, medium SAND, dark yellowish orange (10 YR 6/6), trace coarse Sand, moderate orange pink (5 YR 8/4), strong odor, wet.	Soil color based on Munsell charts. USCS grain size classification.	
22	7	2.0	>2000		Very fine SAND and SILT, dark yellowish brown (10 YR 4/2), light brown (5 YR 4/6) and dusky yellowish brown (10 YR 2/2), strong odor, wet.		
24	8	2.0	>2000		At 23.5 feet, medium to coarse SAND, grayish orange. As above.		
26	9	4.0	158		At 25.5 feet, 0.2 feet of very coarse SAND, medium blueish gray (5 B 5/1). Medium coarse SAND, blueish gray, occasional fine subrounded Gravel, wet.		
28							
30	10	3.0	1561		As above.		
32							
	11	3.0	159		As above.		
34							
					At 35.8 feet, very fine SAND, very pale orange with very dark red (5 R 2/6) banding.		
36	12	2.0	NR		As above.		PID = 56 ppm. Sample lost, jammed in liner.
38	13	2.0	18.6		Very fine SAND to SILT, color as above, trace Clay.		

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-08 / TMW-1 / TMW-1S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/14/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Completion Depth 44 feet bgs	
Geologist(s) Matt Erbe / Brent Williams				Rock Depth NA	
				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES					SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample			
40	14	4.0	15.1			As above to 43.7 feet.	Soil color based on Munsell charts. USCS grain size classification.
42							
						At 43.7 feet, CLAY, grayish orange pink (10 R 8/2) with thin (1/8") very dark red layering.	Basal Clay.
44						End of boring at 44 feet bgs.	
46							Temporary Well Installation TMW-1 Set 1-inch PVC well at 44 feet bgs. 5-foot prepacked screen. Sand to 37 feet bgs. Bentonite to 0 feet bgs.
48							
50							TMW-1S Set 1-inch PVC well at 23.3 feet bgs. 5-foot prepacked screen. Sand to 16 feet bgs. Bentonite to 14 feet bgs.
52							
54							
56							
58							

Environmental Resources Management, Inc.

Boring Log

Boring Number:

NDA-09 / TMW-2 / TMW-2S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/15/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 44 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
0	1	1.5	NR		Fine SAND, light brown (5 YR 5/6), dry.	Soil color based on Munsell charts. USCS grain size classification. NR - Not recorded.
2						
4	2	2.2	NR		Fine SAND, light brown, occasional pebbles and coarse Sand, very dark red (5R 2/6) mottling.	TOC sample
6						
8						
10	3	2.0	NR		As above.	TOC sample
12						
14	4	2.1	NR		As above.	TOC sample
16						
18					At 19 feet, yellow (5 Y 7/6) liquid.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-09/TMW-2/TMW-2S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/15/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 44 feet bgs	
Geologist(s) Matt Erbe / Brent Williams				Rock Depth NA	
North Coordinate				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20	5	3.0	NR		Fine SAND, moderate yellowish brown (10 YR 5/4). Yellow liquid present to 23 feet.	Soil color based on Munsell charts. USCS grain size classification. TOC sample
22						
24						
	6	0.2	NR		Fine to medium SAND, moderate yellowish brown.	TOC sample
26						
28						
30	7	0.0	NR		As above, some discoloration with yellow liquid.	TOC sample
32						
34	8	0.0	NR		Very fine SAND, very pale orange with very dark red (5 R 2/6) banding.	PID = 56 ppm. Sample lost, jammed in liner.
36						
38	9				Very fine SAND to SILT, color as above, trace Clay.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-09 / TMW-2 / TMW-2S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/14/01		Date & Time Completed 3/15/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Sampler(s)		Sampler Depth 4 feet	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Elevation & Datum		Completion Depth 44 feet bgs	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		North Coordinate		Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				East Coordinate			

DEPTH (ft below grade)	SAMPLES					SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample			
40						As above.	Soil color based on Munsell charts. USC5 grain size classification.
42	10					At 44 feet, CLAY, grayish orange pink (10 R 8/2) with thin (1/8") very dark red layering.	Basal Clay.
44						End of boring at 44 feet bgs.	Temporary Well Installations TMW-2 Set 1-inch PVC well at 44 feet bgs. 5-foot prepacked screen. Sand to 37 feet bgs. Bentonite to 15 feet bgs.
46							
48							TMW-2S Set 1-inch PVC well at 23.5 feet bgs. 5-foot prepacked screen. Sand to 17 feet bgs. Bentonite to 15 feet bgs.
50							
52							
54							
56							
58							

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-10

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/15/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/15/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 5 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 5 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 25 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
0	1	3.0	NR		Coarse, flat, iron GRAVEL, very dusky red (10 R 2/2). At 0.5 feet, fine SAND, moderate yellow brown (10 YR 5/4). At 2 feet, fine to medium SAND, moderate yellow brown with moderate red (10 YR 5/4) mottling.	Soil color based on Munsell charts. USCS grain size classification. NR - Not recorded.
2						
4						
	2	3.0	NR		Fine to coarse SAND, pale yellow brown (10 YR 6/2) grades to Clay, yellow gray (5 Y 7/2).	TOC sample
6						
8						
10	3	3.5	NR		Clay, grayish orange (10 YR 7/4), some fine Sand.	TOC sample
12					At 12.8 feet, fine to medium SAND, light brown (5 YR 5/6).	
14						TOC sample
	4	4.0	NR		Silty SAND, moderate brown (5 YR 4/4) to light brown some to little Clay.	
16						
18					At 18 feet, fine to coarse SAND, light brown (5 YR 6/4) occasional subangular medium Gravel.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
NDA-10

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/15/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/15/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 5 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Completion Depth 25 feet bgs	
Geologist(s) Matt Erbe / Brent Williams		North Coordinate		Rock Depth NA	
East Coordinate					

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20	5	0.1	NR		Clay in tip of probe. No sample. Basal clay indicated by NDA-08	Soil color based on Munsell charts. USCS grain size classification. TOC sample
22						
24						
26					End of boring at 25 feet bgs.	Backfilled hole with soil and granular bentonite.
28						
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.

Boring Log

Boring Number:

NDA-11 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 4/19/01	
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar		Date & Time Completed 4/19/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) NA	
Bit Size 2 inch		Core Barrel (s) NA		Sampler Depth NA	
Geologist(s) Matt Erbe		Elevation & Datum		Completion Depth 45 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	FLUTe REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
0					Lithology is based on NDA-08 located ~15 feet west. Fine SAND, light brown (5 YR 5/6), strong odor, dry.	Soil color based on Munsell charts. USCS grain size classification.
2						
4					Fine SAND, light brown, occasional pebbles, strong odor, dry.	
6						
8					At 7 feet, Silty SAND, grayish orange (10 YR 7/4), trace Clay.	
10					As above, wood fragments, grades to light brown, strong odor, moist.	8.75 - 12.0 feet; amber colored product, oily appearance, wicks dye to edges.
12					Fine SAND, moderate brown (5 YR 3/4 to 4/4), little Silt, occasional coarse Gravel, strong odor, wet.	12.0 - 14.9 feet; product from above interval migrating downward along FLUTe liner as indicated by stream and several small globules between 12.7 and 13.5 feet.
14					As above, pushed Gravel from 16 feet to 18 feet.	
16						
18					As above with iron concretions to 18.5 feet. At 18.5 feet, medium SAND, dark yellowish orange (10 YR 6/6), trace coarse Sand, moderate orange pink (5 YR 8/4), strong odor, wet.	17.9 - 18.3 feet; small amber color globules. 18.7 - 20.5 feet; solid zone of amber color product as above.

Environmental Resources Management, Inc.

Boring Log

Boring Number:

NDA-11 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 4/19/01		Date & Time Completed 4/19/01	
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar		Sampler(s)		Sampler Depth NA	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Elevation & Datum		Completion Depth 45 feet bgs	
Bit Size 2 inch		Core Barrel (s) NA		North Coordinate		Rock Depth NA	
Geologist(s) Matt Erbe				East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	FLUTe REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20					Lithology is based on NDA-08 located ~15 feet west. At 18.5 feet, medium SAND, dark yellowish orange (10 YR 6/6), trace coarse Sand, moderate orange pink (5 YR 8/4), strong odor. <u>Water table at 21 feet.</u>	20.5 - 23.5 feet; product from above interval migrating downward along FLUTe liner as indicated by stream. 22.3 - 22.5 feet; very small globules.
22					Very fine SAND and SILT, dark yellowish brown (10 YR 4/2), light brown (5 YR 4/6) and dusky yellowish brown (10 YR 2/2), strong odor, wet. At 23.5 feet, medium to coarse SAND, grayish orange. As above.	23.1 - 23.6 feet; amber globules.
24					At 25.5 feet, 0.2 feet of very coarse SAND, medium blueish gray (5 B 5/1).	24.3, 24.6, 24.8 feet; dots of free product.
26					Medium coarse SAND, blueish gray, occasional fine subrounded Gravel, wet.	25.3 and 25.7 feet; dots of free product.
28						28.9 feet; dot of free product.
30					As above.	
32					As above.	32.1 feet; dot of free product. 33.1 feet; small globule.
34					At 35.8 feet, very fine SAND, very pale orange with very dark red (5 R 2/6) banding.	34.4 feet; small globule.
36					As above.	37.0 - 37.5 feet; dots of free product.
38					Very fine SAND to SILT, color as above, trace Clay.	

Environmental Resources Management, Inc.

Boring Log

Boring Number:

NDA-11 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 4/19/01	
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar		Date & Time Completed 4/19/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) NA	
Bit Size 2 inch		Core Barrel (s) NA		Sampler Depth NA	
Geologist(s) Matt Erbe		Elevation & Datum		Completion Depth 45 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	FLUTe REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
40					As above to 43.7 feet.	
42						41.5 feet; dot of free product.
44					At 43.7 feet, CLAY, grayish orange pink (10 R 8/2) with thin (1/8") very dark red layering.	42.8 - 43.0 feet; dots of free product.
					End of boring NDA-08 at 44 feet bgs.	
					End of boring NDA-11 at 45 feet bgs.	
46						
48						
50						
52						
54						
56						
58						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-19

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 26 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
0	1	2.3	*		Fine to coarse SAND, moderate reddish brown (10 R 4/6) to very dark red (5 R 2/6), dry.	Soil color based on Munsell charts. USCS grain size classification. *PID reading not collected. See also the log for adjacent boring PO2-01 for lithology.
2						
4	2	1.7	>2000		Fine SAND, light brown (5 YR 5/6), some Silt, occasional coarse Sand, very moist.	
6						
8	3	0.0	*		Medium to coarse SAND, moderate yellowish brown, little Silt and fine Sand, very moist.	*PID reading not collected. Very loose. No recovery.
10					At 10 feet, dusky brown (5 YR 2/2) to grayish black (N2) staining, wet.	TCLP metals sample Total RCRA metals sample
12	4	3.0	>2000		Fine to coarse SAND, medium dark gray (N4), little fine subangular to subround Gravel, odor, wet.	
14	5	3.0	>2000		Recollected samples on 3/19/01 starting at 14 feet. Medium to coarse SAND, fining downward, dark gray staining, odor, wet.	
16						
18	6	4.0	>2000		Coarse SAND to fine GRAVEL, gray stained, wet.	PID < 20 ppm at bottom.

Environmental Resources Management, Inc.

Boring Log

Boring Number:

PO2-19

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 26 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
20						Soil color based on Munsell charts. USCS grain size classification.
22	7	4.0	0		As above.	
24					At 24 feet, CLAY, moderate reddish orange (10 R 6/6) to grayish orange pink (10 R 8/2).	
26					End of boring at 26 feet bgs.	Temporary Well Installations TMW-5 Set 1-in PVC well at 22.5 feet bgs w/ 5 feet prepacked well screen Sand to 15 feet bgs Bentonite to 0 feet bgs TMW-5S Set 1-in PVC well at 13 feet bgs w/ 5 feet prepacked well screen Sand to 6 feet bgs Bentonite to 2 feet bgs
28						
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-20

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler Depth 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 28 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
0	1	3.0	*		Fine to coarse SAND, moderate reddish brown (10 R 4/6) to very dark red (5 R 2/6), dry.	Soil color based on Munsell charts. USCS grain size classification. *PID reading not collected.
2						
4	2	2.0	*		Fine SAND, light brown (5 YR 5/6), some Silt, occasional coarse Sand, very moist.	TOC sample *PID reading not collected.
6						
8	3	4.0	*		Medium to coarse SAND, moderate yellowish brown, little Silt and fine Sand, very moist.	TOC sample *PID reading not collected.
10					At 10 feet, dusky brown (5 YR 2/2) to grayish black (N2) staining, wet.	
12	4	2.8	>2000		Fine to coarse SAND, medium dark gray (N4), little fine subangular to subround Gravel, odor, wet.	TOC sample
14						
16	5	4.0	>2000		As above.	TOC sample
18						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-20

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 28 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
20	6	4.0	0		Coarse SAND and fine GRAVEL, little Silt, wet.	Soil color based on Munsell charts. USCS grain size classification.
22					At 22 feet, Clayey medium SAND.	
24	7	4.0	0		Clayey medium SAND to Clayey SILT, grayish orange pink (10 R 8/2).	
26					At 27.5 feet, grayish orange pink CLAY with very dark red (5 R 2/6) banding.	Backfilled borehole with granular bentonite.
28					End of boring at 28 feet bgs.	
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-21

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/20/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) Sampler Depth 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 30 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe				North Coordinate East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
0	1	3.4	0		0.2 ft TOPSOIL (grass, dark brown Silt), then fine to coarse SAND and angular GRAVEL, light brown (5YR 5/6), few ironstone chips, dry.	Soil color based on Munsell charts. USCS grain size classification.
2						
4	2	3.0	0		As above to 4.5 feet then fine SAND with increasing Silt, grayish orange (10 YR 7/4).	TOC sample Pushed sampler 4-9 feet
6						
8					At 8.5 feet, gray (N3) staining	
	3	4.0	41.9		Silty fine to medium SAND, grayish orange, dry.	TOC sample Pushed sampler 9-14 feet.
10					At 10.5 feet, fine SAND, dark gray (N2), slight odor, moist.	
12						
14	4	4.0	>2000		Medium to coarse SAND as above to 17.5 feet.	TOC sample
16					Coarse SAND, very pale orange (10 YR 8/2), little fine to medium subround to subangular Gravel, odor, wet.	
18	5	3.0	949		Medium SAND, well graded at top to poorly graded at bottom, dark gray, odor, wet.	TOC sample

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-21

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/20/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/20/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 30 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
20						Soil color based on Munsell charts. USCS grain size classification.
22	6	2.0	*		Coarse SAND and fine GRAVEL, light olive brown (5 Y 5/6), little fine Sand, trace Silt and Clay, wet.	*PID reading not collected. TOC sample
24						
26	7	0.2	*		Fine to coarse SAND, light olive brown, wet.	*PID reading not collected. Sample fell out of sleeve. Enough to collect TOC sample
28						
					"Clay" at 30 feet. (increased difficulty advancing)	
30					End of boring at 30 feet bgs.	Backfilled borehole with granular bentonite.
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-22 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 4/18/01	
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar		Date & Time Completed 4/18/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) NA	
Bit Size 2 inch		Core Barrel (s) NA		Sampler Depth NA	
Geologist(s) Matt Erbe				Elevation & Datum Completion Depth 25 feet bgs Rock Depth NA	
North Coordinate		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	FLUTe Remarks
	Sample Number	Recovery (feet)	FID/ PID (ppm)	Lab Sample		
0					See log PO2-19 located about 10 feet south for similar lithology.	No evidence of free product observed at this location.
4					End of Boring B-36 at 25 feet bgs.	
8					End of Boring B-36 at 25 feet bgs.	
12					End of Boring B-36 at 25 feet bgs.	
16					End of Boring B-36 at 25 feet bgs.	
20					End of Boring B-36 at 25 feet bgs.	
24					End of Boring B-36 at 25 feet bgs.	
28					End of Boring B-36 at 25 feet bgs.	
32					End of Boring B-36 at 25 feet bgs.	
36					End of Boring B-36 at 25 feet bgs.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
PO2-23 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 4/18/01	
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar		Date & Time Completed 4/18/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) NA	
Bit Size 2 inch		Core Barrel (s) NA		Sampler Depth NA	
Geologist(s) Matt Erbe		Elevation & Datum		Completion Depth 25 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	FLUTe Remarks
	Sample Number	Recovery (feet)	FID/PID (ppm)	Lab Sample		
0						No evidence of free product observed at this location.
4						
8						
12						
16						
20						
24						
					End of Boring at 25 feet bgs.	
28						
32						
36						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-23 / TMW-6 / TMW-6S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 27 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS	
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample			
0	1	2.7	0		Fine SAND, light to moderate brown (5 YR 4/4), little silt, dry.	Soil color based on Munsell charts. USCS grain size classification. See also log for adjacent BWA-01	
2					At 2.1 feet, Fine to medium SAND with pale orange (10 YR 8/2) silt laminations, angular ironstone and round pebbles throughout, dark reddish brown (10 R 3/4) mottling, moist.		
4	2	4.0	1569		CLAY, light gray (N7), with medium sand laminations, moderate yellowish brown (10 YR 5/4) with moderate reddish brown (10R 4/6) mottling, slight odor, dry.		
6							
8							
	3	0.6	35.1		As above.		
10							TCLP metals sample RCRA metals sample
12							
	4	3.0	1581		SILT, grayish orange pink (10 R 8/2), some clay, trace fine sand, moist.		
14					At 13.7 feet, very fine SAND and SILT, very pale orange (10 YR 8/2).		
16	5	4.0	>2000		As above to 17.5 feet, strong odor. Then fine SAND, very pale orange, some silt.		
					At 18.5 feet, 0.5 foot zone with beads of brown residual product.		
18							
					At 19 feet fine SAND, gray (N5), no evidence of product.		

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-23 / TMW-6 / TMW-6S

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) Sampler Depth 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 27 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20	6	4.0	>2000		Medium SAND, light gray (N7), wet.	Soil color based on Munsell charts. USCS grain size classification.
					At 21.4 feet very fine Silty SAND, light gray, brown residual product.	
22					At 22.7 feet Silty medium SAND, trace Clay, no evidence of residual product, strong odor.	
24	7	3.0	1029		SAND, very pale orange, several thin (0.25-in) Clayey Silt laminations throughout, occasional ironstone pebble, flat 2-in diameter, strong odor.	
26					At 26.5 feet grades to very fine SAND and SILT, moderate reddish brown.	
					At 26.8 feet CLAY, moderate reddish brown, some very fine Sand and Silt laminations.	
28					End of boring at 27 feet bgs.	Temporary Well Installations TMW-6 Set 1-in PVC well at 25.4 feet bgs w/ 5 feet prepacked well screen Sand to 19.5 feet bgs Bentonite to 17 feet bgs TMW-6S Set 1-in PVC well at 16.9 feet bgs w/ 5 feet prepacked well screen Sand to 10 feet bgs Bentonite to 8 feet bgs
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-24

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Elevation & Datum Completion Depth 28 feet bgs Rock Depth NA	
Geologist(s) Matt Erbe / Brent Williams				North Coordinate	
				East Coordinate	

DEPTH (ft below grade)	SAMPLES					SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample			
0	1	3.0	NR			Fine to coarse SAND, yellowish brown (10 YR 5/4).	Soil color based on Munsell charts. USCS grain size classification. NR - Not recorded.
2							
4	2	3.0	NR			As above, iron pebbles from 4 to 6 feet.	TOC sample
6							
8	3	1.5	NR			Fine to medium SAND, grayish brown (5 YR 3/2) grading to pale yellowish brown (10 YR 6/2), little Silt, dry.	TOC sample
10							
12	4	3.0	NR			As above, gray (N5) staining.	TOC sample
14						At 14 feet, Silty fine SAND, pale yellowish brown with light gray (N7) staining, moist.	
16	5	3.0	NR			Silty fine SAND, light gray with some dark gray (N3) mottled staining.	TOC sample
18							

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-24

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Completion Depth 28 feet bgs	
Geologist(s) Matt Erbe / Brent Williams		North Coordinate		Rock Depth NA	
East Coordinate					

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20	6	3.0	NR		Silty fine SAND, light brown (5YR 5/6) to medium gray (N5), wet.	Soil color based on Munsell charts. USCS grain size classification.
22						
					At 23.5 feet, increasing Clay, reddish brown (10 R 4/6).	TOC sample
24	7	3.0	NR		As above, increasing Clay.	
26					At 26.5 feet, CLAY.	TOC sample
28					End of boring at 28 feet bgs.	
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-25

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 28 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
0	1	1.0	NR		Fine to coarse SAND and fine to medium, angular GRAVEL, moderate yellowish brown (10 YR 5/4), dry.	Soil color based on Munsell charts. USCS grain size classification. NR - Not recorded.
2						
4	2	4.0	NR		As above, moderate yellowish brown to grayish brown (5 YR 3/2), occasional iron pebbles throughout, moist to dry.	TOC sample
6						
8	3	4.0	NR		Medium to coarse SAND, pale yellowish brown (10 YR 6/2), little Silt, trace Clay, occasional fine to medium Gravel, dry to moist.	TOC sample
10						
12	4	4.0	NR		At 11.5 feet, light gray clay (N7). Fine to medium SAND, pale yellowish brown.	TOC sample
14					At 13 feet, increasing Silt to Silty fine SAND, pale reddish brown (10 R 5/4) to pale yellowish brown, little Clay. Wet at 14 feet.	
16	5	4.0	NR		Fine to medium SAND, pale yellowish brown, trace Silt, wet.	TOC sample
18					At 17.5 feet, Silty very fine SAND, light gray.	
					At 19.5 feet, pale reddish brown mottling, black specs.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-25









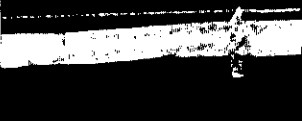
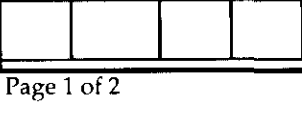
Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01		Date & Time Started 3/13/01	
Drilling Company Tidewater, Inc.		Driller Pete Miller		Date & Time Completed 3/13/01	
Drilling Equipment Geoprobe 66DT		Method Direct-Push		Sampler(s) 4 feet	
Bit Size 2 inch		Core Barrel (s) 4-foot soil core		Sampler Depth 4 feet	
Geologist(s) Matt Erbe / Brent Williams		Elevation & Datum		Completion Depth 28 feet bgs	
		North Coordinate		Rock Depth NA	
		East Coordinate			

DEPTH (ft below grade)	SAMPLES				SOIL DESCRIPTION	REMARKS
	Sample Number	Recovery (feet)	PID (ppm)	Lab Sample		
20	6	4.0	NR		As above.	Soil color based on Munsell charts. USCS grain size classification. TOC sample at 20 feet.
					At 21.5 feet very fine SAND and SILT, yellowish gray (5 Y 7/2).	
22					At 23.8 feet pale reddish brown to dark yellowish brown (10 YR 4/2) mottling.	
24	7	4.0	NR		As above.	
26					At 27 feet CLAY, light gray and moderate reddish brown (10 R 4/6).	
28					End of boring at 28 feet bgs.	
30						
32						
34						
36						
38						

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-26 (FLUTe)



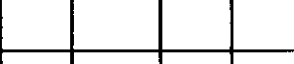



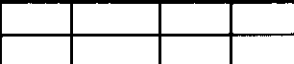

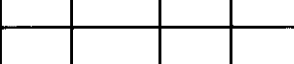
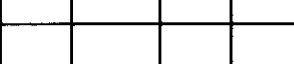


Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01	Date & Time Started 4/18/01
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar	Date & Time Completed 4/19/01
Drilling Equipment Geoprobe 66DT		Method Direct-Push	Sampler(s) NA
Bit Size 2 inch		Core Barrel (s) NA	Sampler Depth NA
Geologist(s) Matt Erbe		Elevation & Datum	Completion Depth 28 feet bgs
		North Coordinate	Rock Depth NA
		East Coordinate	

DEPTH (ft below grade)	FLUTe Photo Log	SOIL DESCRIPTION	FLUTe REMARKS
0		Lithology is based on BWA-23 located ~30 feet south. Fine SAND, light to moderate brown (5 YR 4/4), little Silt, dry.	Soil color based on Munsell charts. USCS grain size classification.
2		At 2.1 feet, Fine to medium SAND with pale orange (10 YR 8/2) Silt laminations, angular ironstone and round pebbles throughout, dark reddish brown (10 R 3/4) mottling, moist.	
4		CLAY, light gray (N7), with medium Sand laminations, moderate yellowish brown (10 YR 5/4) with moderate reddish brown (10R 4/6) mottling, slight odor, dry.	
6			
8		As above.	
10			
12		SILT, grayish orange pink (10 R 8/2), some Clay, trace fine Sand, moist. Water table at about 13 feet.	11.0 - 11.5 feet; globules of free product, slight discoloration, wicks dye.
14		At 13.7 feet, very fine SAND and SILT, very pale orange (10 YR 8/2).	12.1 - 13.1 feet; several spaced dots. Highly concentrated from 12.6 - 12.8 feet. Large dot to globule at 13.3 feet.
16		As above to 17.5 feet, strong odor. Then fine SAND, very pale orange, some Silt. At 18.5 feet, 0.5 foot zone with beads of brown residual product.	
18		At 19 feet fine SAND, gray (N5), no evidence of product.	

Environmental Resources Management, Inc.
Boring Log

Boring Number:
BWA-26 (FLUTe)

Site Name & Location MD Sand Gravel & Stone		Project Number 48410.01	Date & Time Started 4/18/01
Drilling Company Columbia Technologies, LLC		Driller Eric Magdar	Date & Time Completed 4/19/01
Drilling Equipment Geoprobe 66DT		Method Direct-Push	Sampler(s) NA
Bit Size 2 inch		Core Barrel (s) NA	Sampler Depth NA
Geologist(s) Matt Erbe		Elevation & Datum Completion Depth 28 feet bgs Rock Depth NA	
		North Coordinate	
		East Coordinate	

DEPTH (ft below grade)	FLUTe Photo Log	SOIL DESCRIPTION	FLUTe Remarks
20		Medium SAND, light gray (N7), wet.	
22		At 21.4 feet very fine Silty SAND, light gray, brown residual product.	
		At 22.7 feet Silty medium SAND, trace Clay, no evidence of residual product, strong odor.	
24		SAND, very pale orange, several thin (0.25-in) Clayey Silt laminations throughout, occasional ironstone pebble, flat 2-in diameter, strong odor.	
26		At 26.5 feet grades to very fine SAND and SILT, moderate reddish brown.	
		At 26.8 feet CLAY, moderate reddish brown, some very fine Sand and Silt laminations.	
28		End of BWA-23 boring at 27 feet bgs. End of BWA-26 boring at 28 feet bgs.	
30			
32			
34			
36			
38			

B

Appendix B
Membrane Interface Probe
Survey (MIPS)

APPENDIX B - MEMBRANE INTERFACE PROBE SURVEY

ERM subcontracted COLUMBIA Technologies, LLC to conduct a Membrane Interface Probe (MIP) Survey around the three principal threat areas at the Maryland Sand, Gravel and Stone site in Elkton, Maryland. The data was collected on 19 and 20 April 2001 using a Geoprobe® 66DT to drive the probe to the target depth. The MIP profiles are identified as follows:

- Northern Depression Area - NDA-12 and NDA-13;
- Buried Waste Area - BWA-27 and BWA-28; and
- Pond 02 Area - P02-24 and P02-25.

The following MIP profiles are presented in two formats. The standard format uses a consistent scale between all holes to compare results sitewide. The best format uses separate scales optimized to help in interpreting the results for each location. Each data set from each location consists of the following profiles:

1. Electrical Conductivity Log - Provides an indication of soil type. Readings were collected every 0.05 foot. Low conductivity usually reflects coarser grained sediments, such as sand and gravel, and higher conductivity usually reflects finer grained sediments, such as silts and clays. A change in mineralogy of the soil particles may also change the conductivity. The conductivity ranges for sediments typically average 0.1-2 millisiemens per meter (mS/m) for sand, 3-20 mS/m for silt, and 9-1000 mS/m for clay. Typically, a conductivity log is obtained and then compared with soil core or existing lithologic data to determine the log response to various strata. For the Maryland Sand Gravel and Stone site the typical conductivity ranges were interpreted from existing lithologic data as follows:
 - Sand - 0.1-2 mS/m;
 - Sand and sand-silt mixtures - 2-10 ms/m; and
 - Clay and sand-silt-clay mixtures - 10 to 30 mS/m.
2. Penetration Rate Log (Speed) - Provides an indication of resistance to probe penetration. Ideally the probe is pushed with a Geoprobe® rig.

Hammering the probe will cause short elevated responses. Speed is measured in feet per minute.

3. PID Log (Detector 1) – The photo-ionization detector is sensitive to the aromatic compounds such as BTEX and some solvents, such as PCE and TCE. The response is measured in microvolts (uV).

FID Log (Detector 2) – The flame-ionization detector is sensitive to methane and fuel constituents. The response is measured in uV.

ECD Log (Detector 3) – The electron capture detector is sensitive to a wide range of chlorinated solvents. The response is measured uV.

The MIP is considered to be a semi-quantitative tool; the response of the detectors will vary in the subsurface depending upon the soil media and organic carbon content, soil water content, and volatility of the contaminant being detected. Readings were collected every 0.05 foot, however, one foot depth intervals were selected to best profile contamination at each location. For example, the probe was advanced from 10 to 11 feet below grade and allowed to burn off any volatiles prior to advancing from 11 to 12 feet.

For use in comparison to the MIP *in-situ* profile data two soil samples, BWA-27 4 feet and 11 feet, were analyzed for VOCs. The 4 feet sample was collected from a sand layer and the 11 feet sample was collected from a silty clay layer, each above the water table. Each sample was targeted for a soil interval displaying a moderate to high response on the ECD. The following table summarizes the relative response (uV) of the FID, PID and ECD detectors along with the total BTEX and chlorinated VOC concentrations (mg/kg) reported by the analytical laboratory.

MIP/VOC Comparison Soil Samples

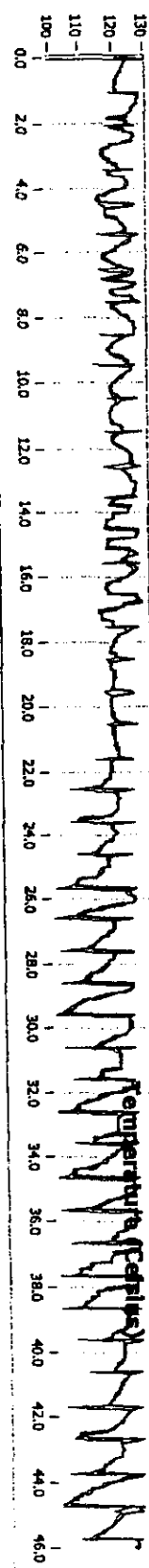
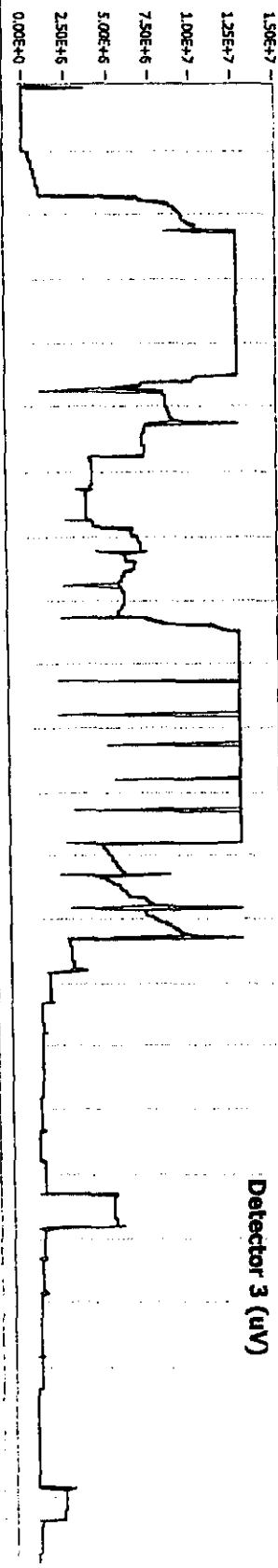
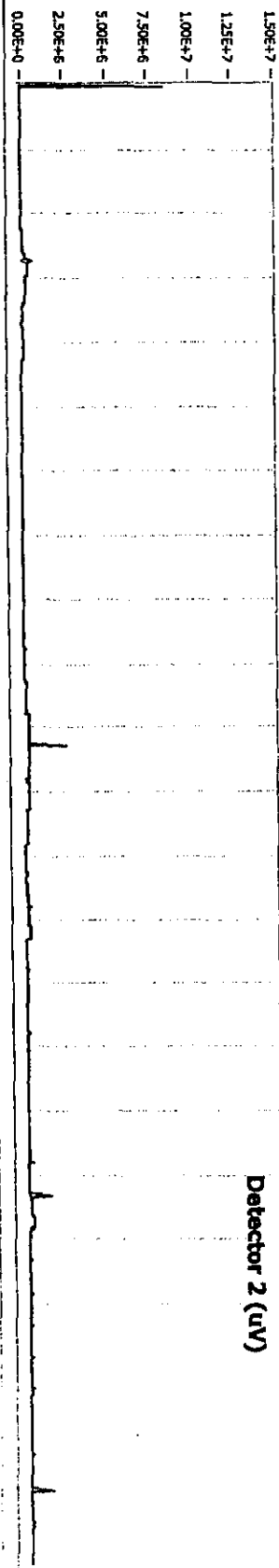
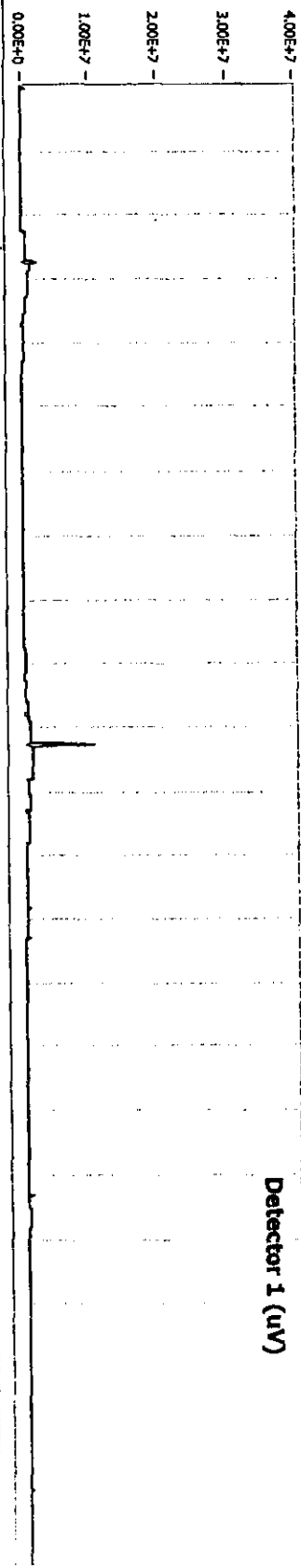
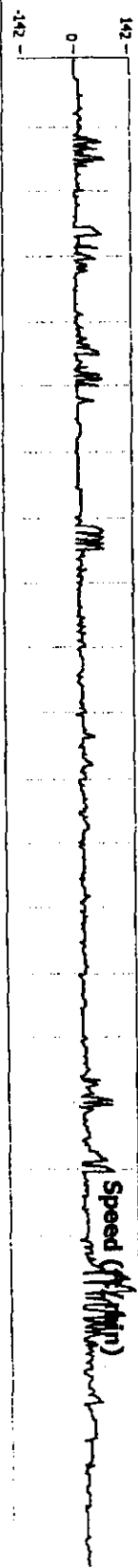
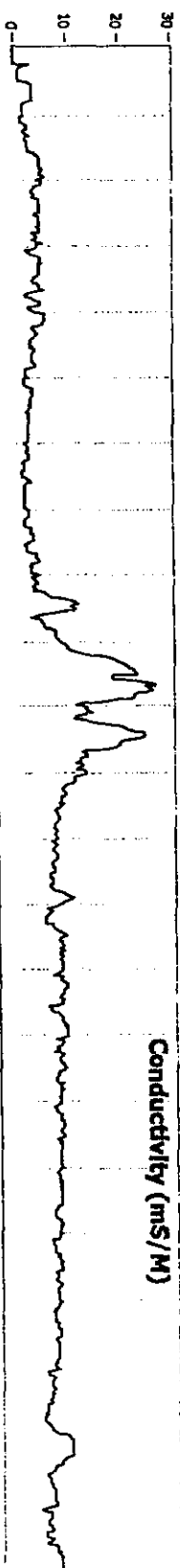
Analysis	BWA-27, 4 feet (Sand)	BWA-27, 11 feet (Silt and Clay)
FID (uV)	20,714	3,576,338
PID (uV)	46,349	951,785
ECD (uV)	3,527,508	12,804,991 *
Total BTEX (mg/kg)	0	38.7
Total CVOCs (mg/kg)	33.4	91.7

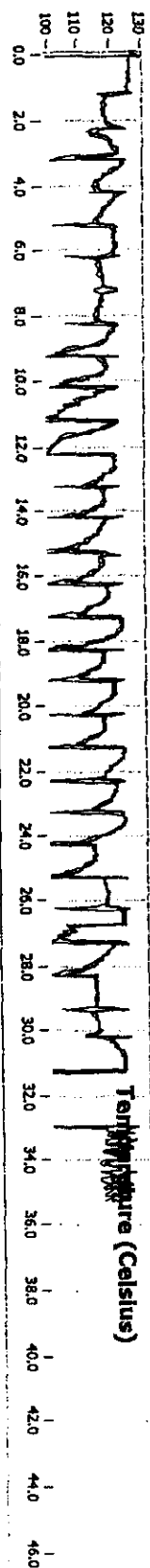
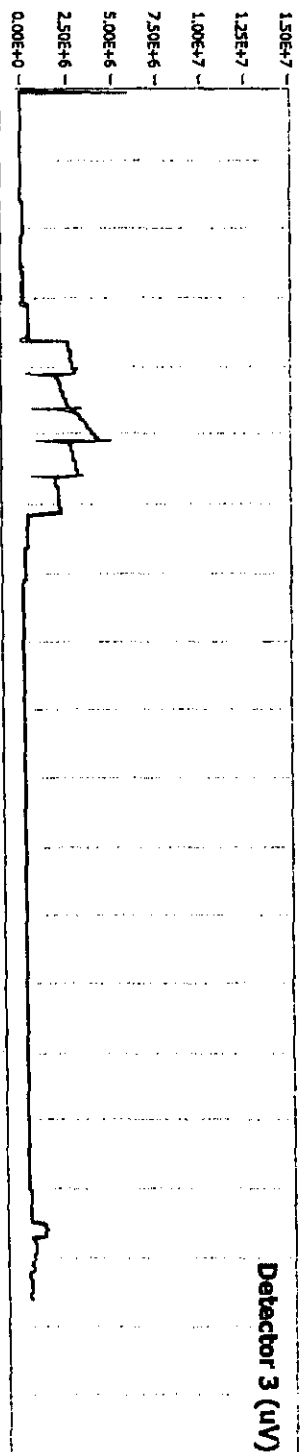
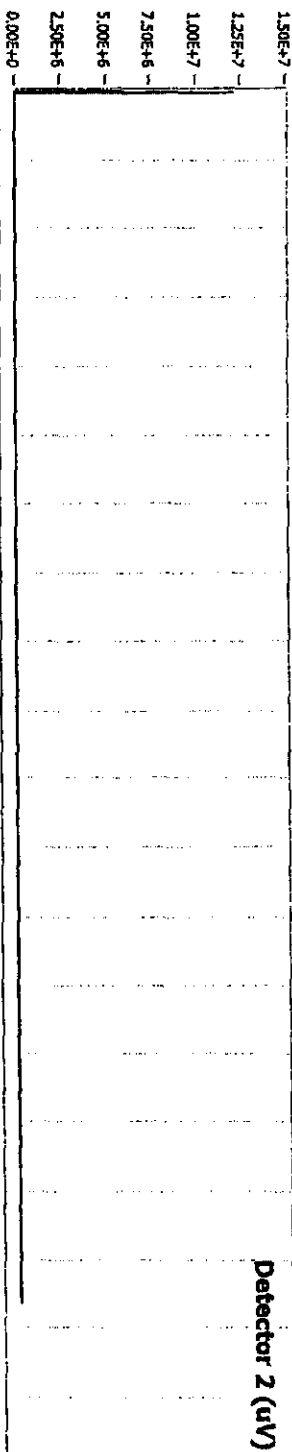
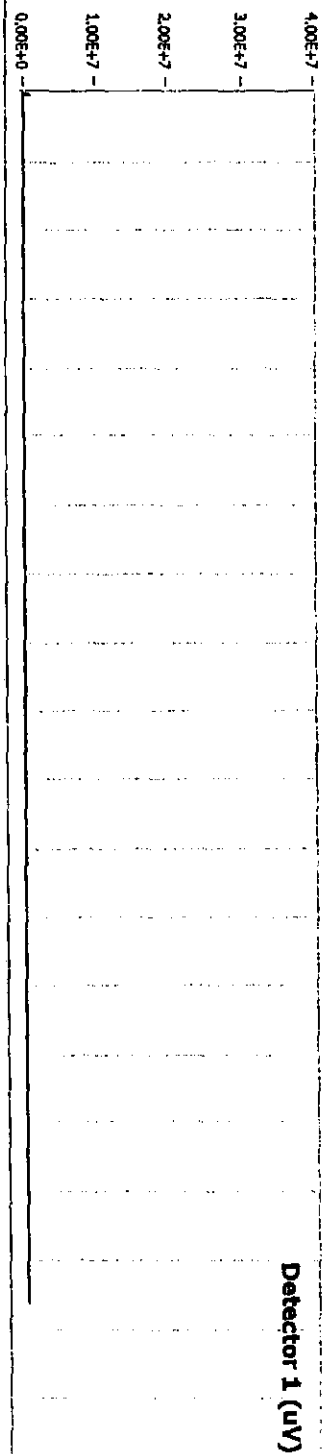
Total BTEX – sum of benzene, toluene, ethylbenzene and xylene concentrations.

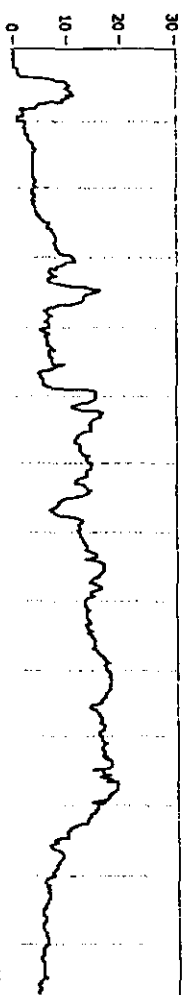
Total CVOCs – sum of eight detected chlorinated VOC concentrations.

* The maximum ECD instrument response was limited to 12,804,991 mV.

4. Temperature Log - Can often be used to locate the water table and more saturated zones. The output is the temperature of the probe (100-120 °C) which is causing the compounds to volatilize. A quick and/or large decrease in temperature results as the probe enters cooler water of the deeper advancing interval.



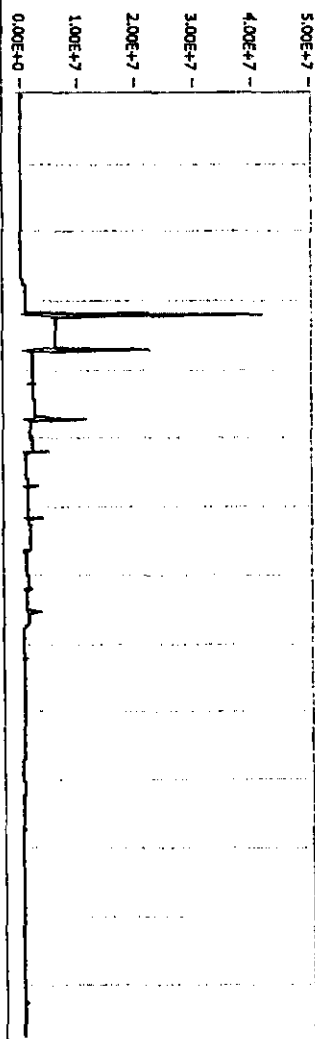




Conductivity (mS/M)



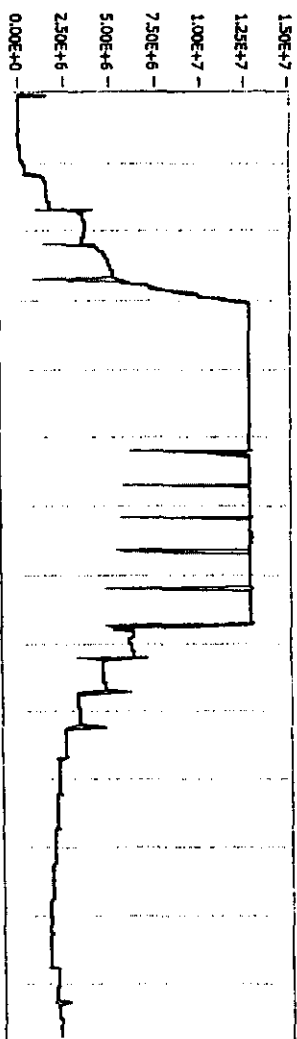
Speed (ft/min)



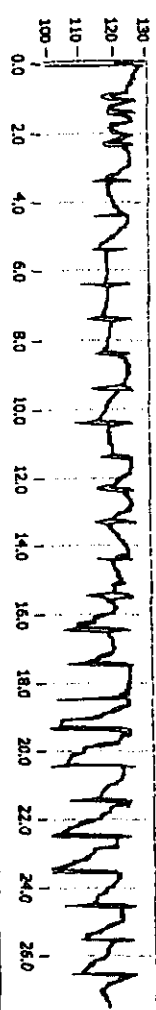
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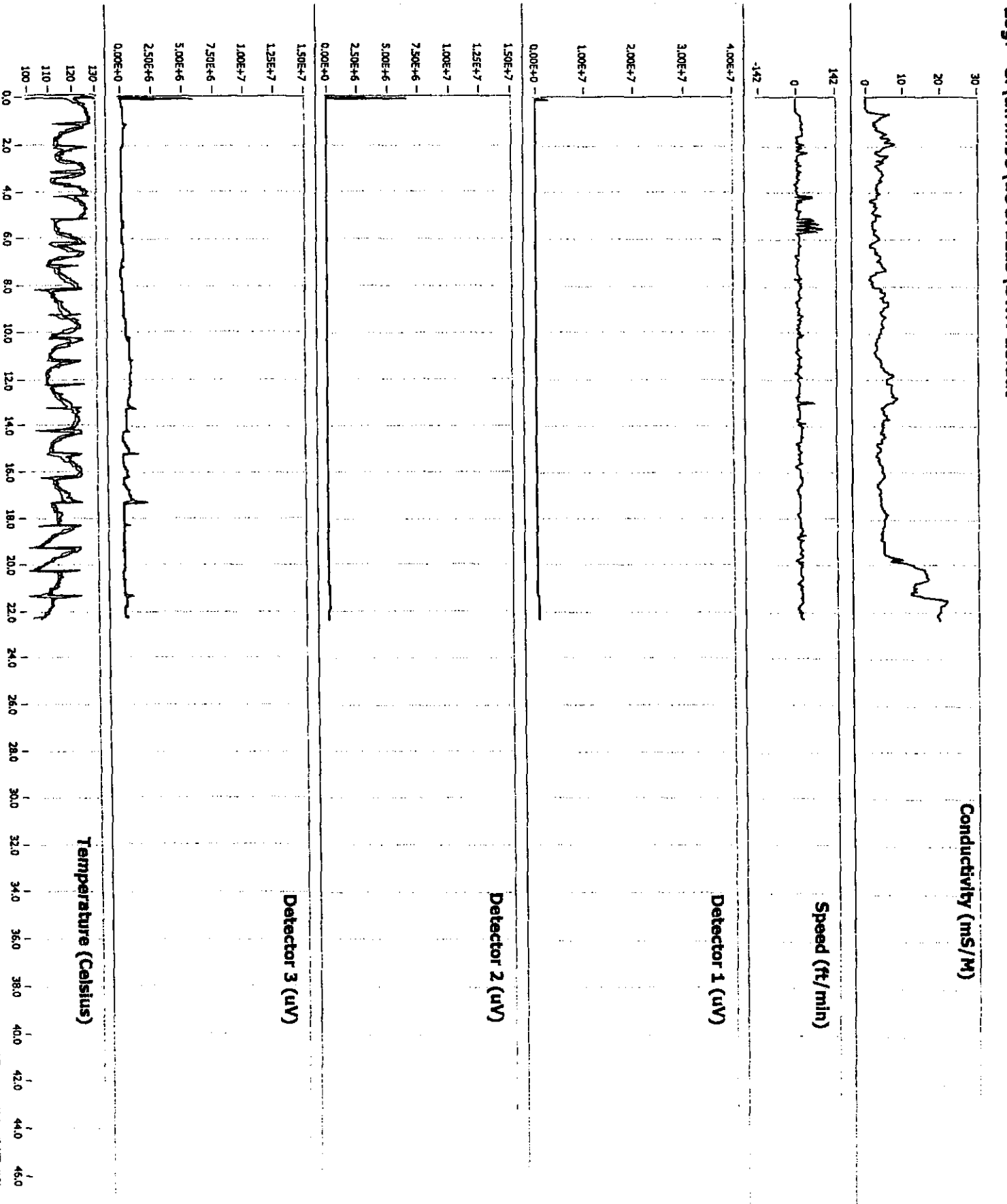
Detector 2 (uV)

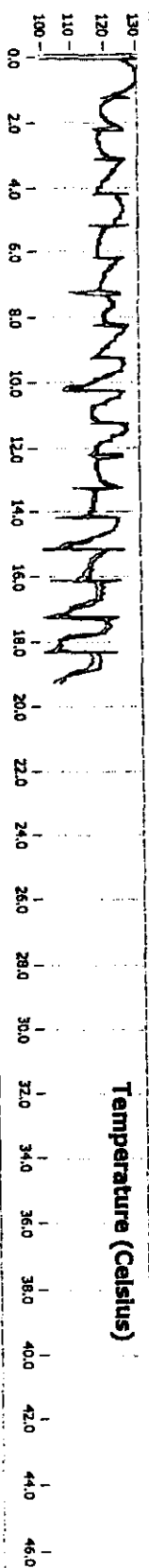
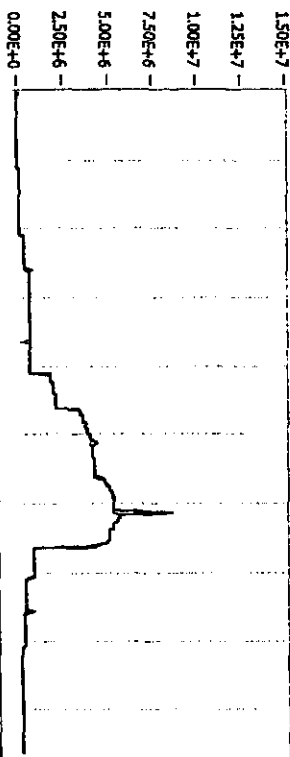
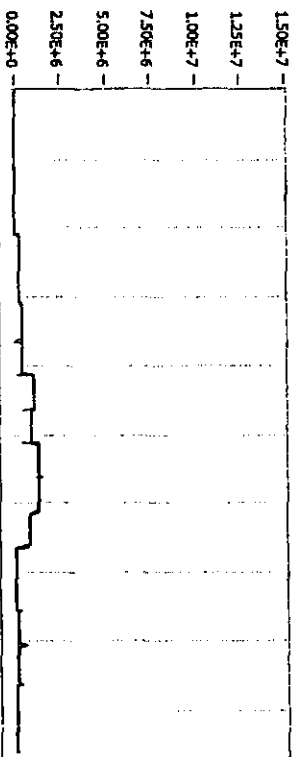
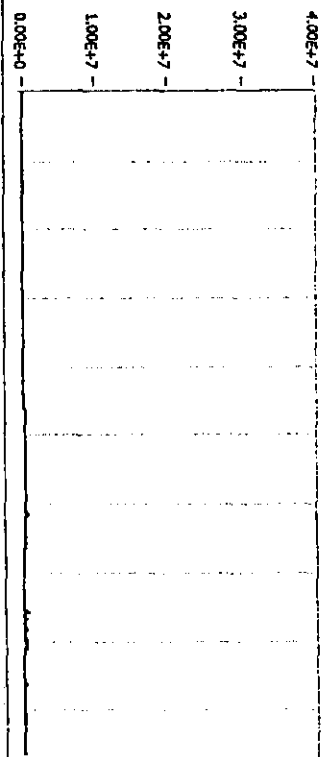
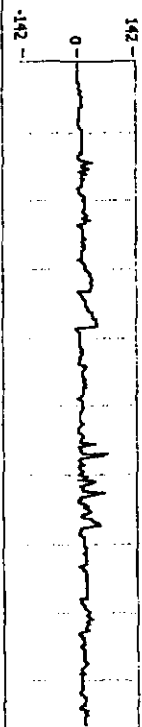
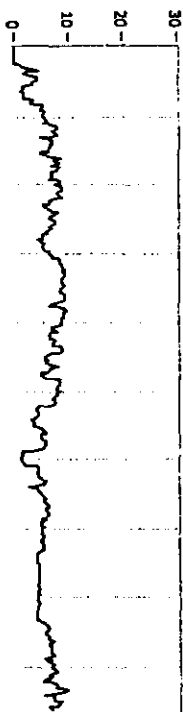


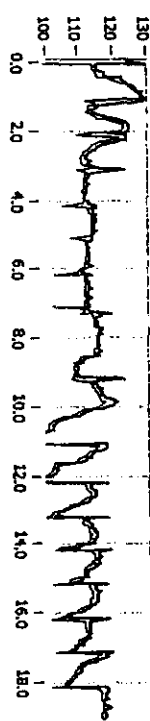
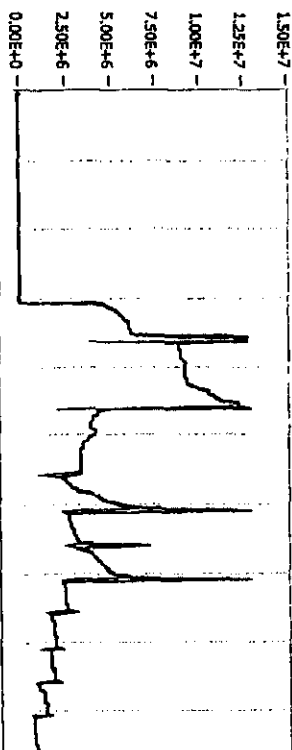
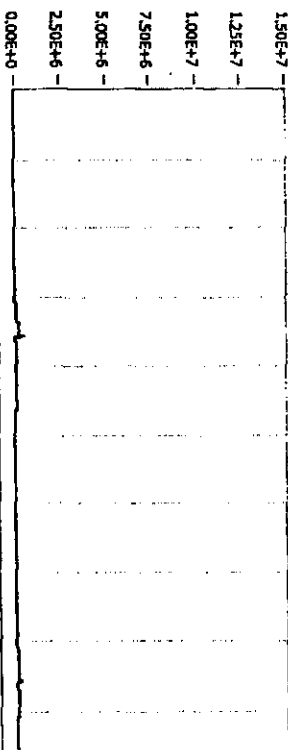
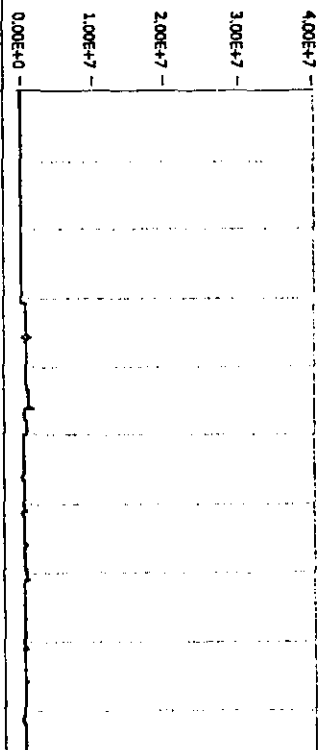
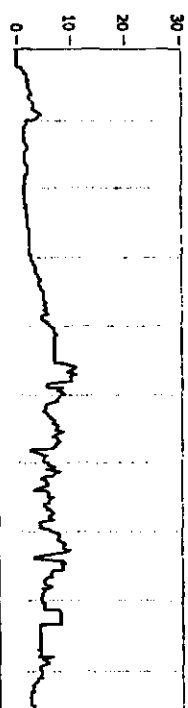
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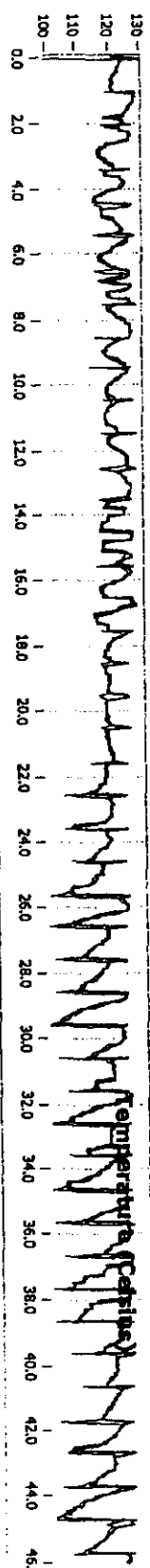
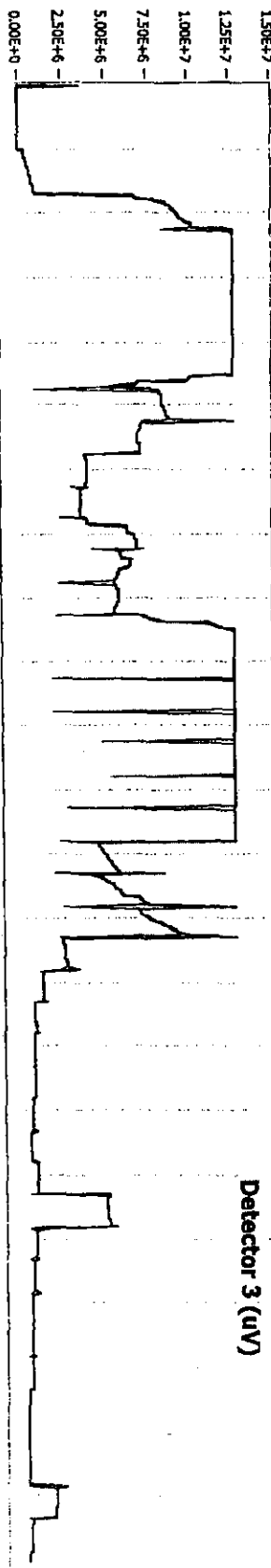
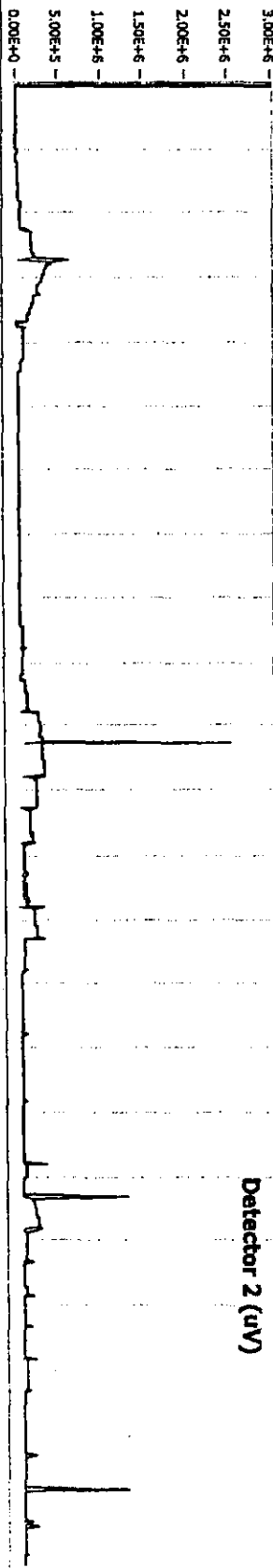
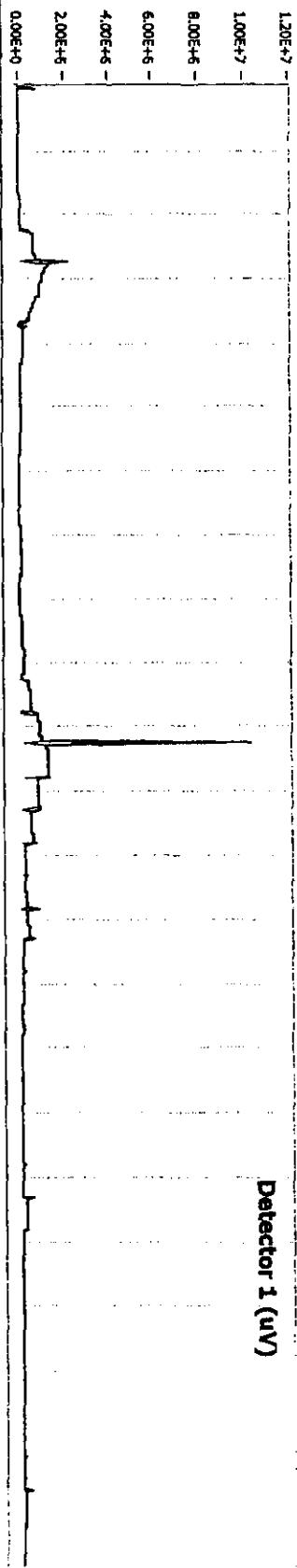
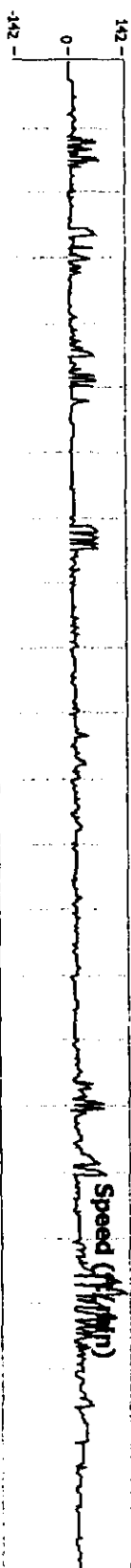
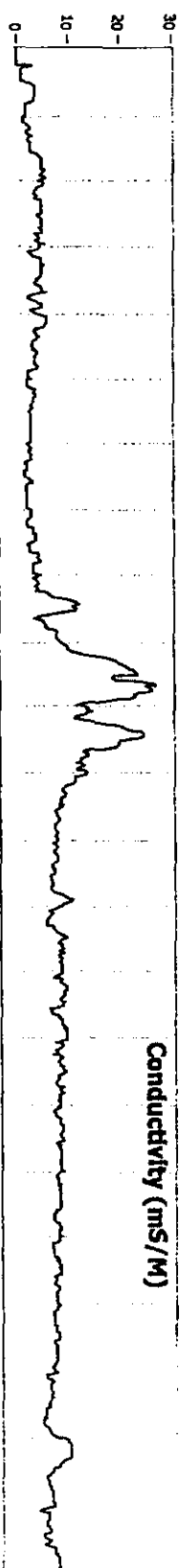


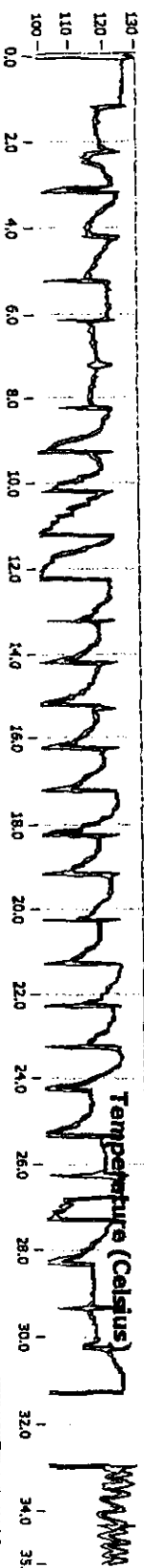
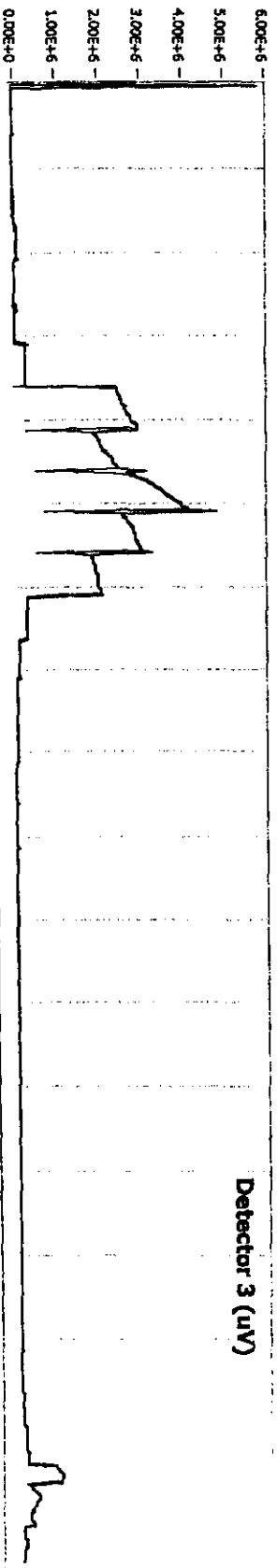
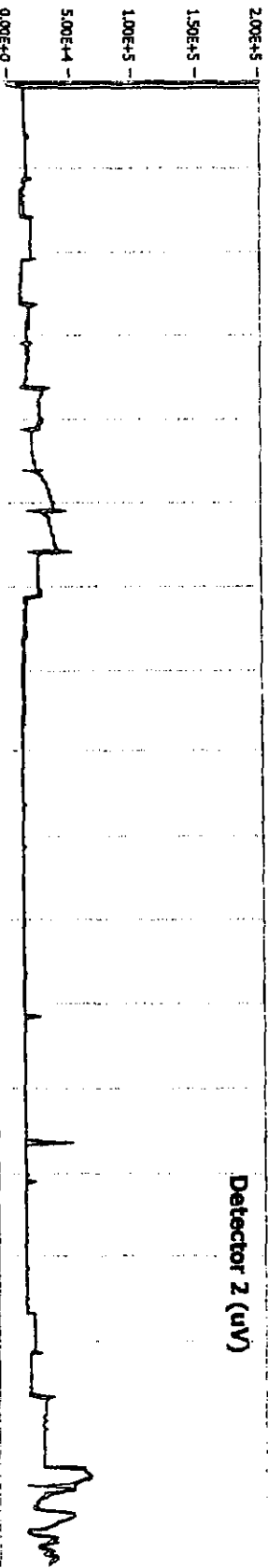
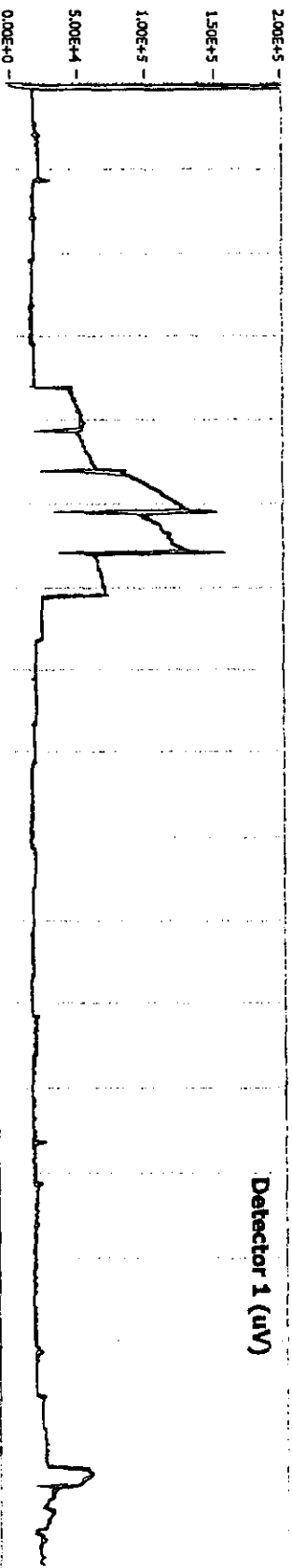
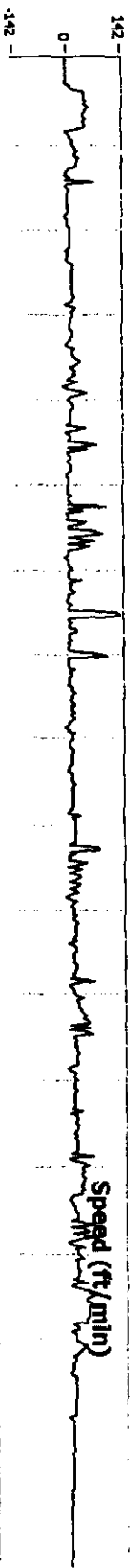
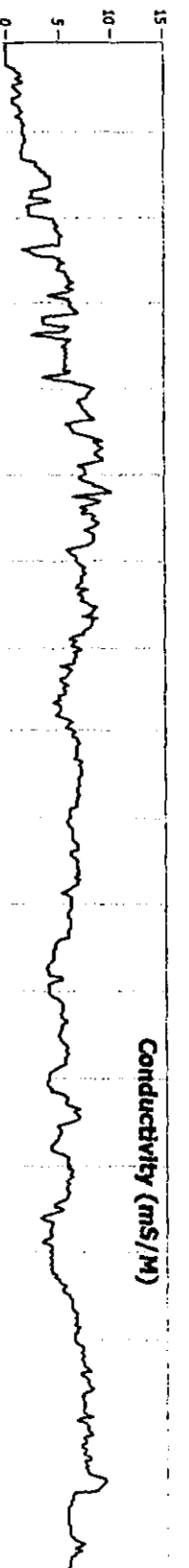
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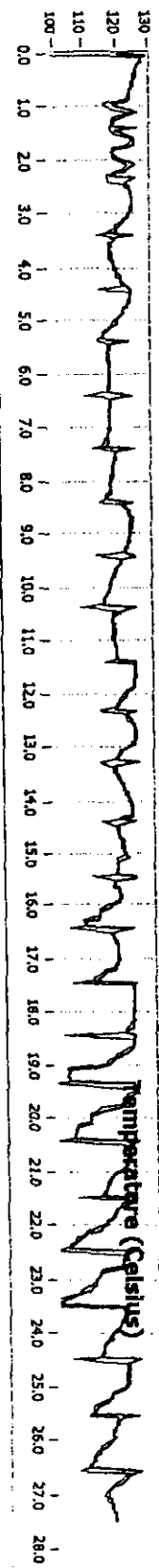
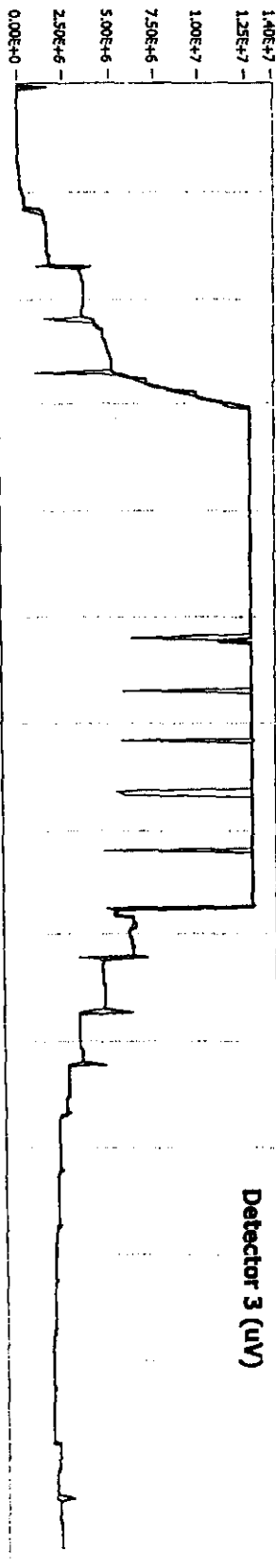
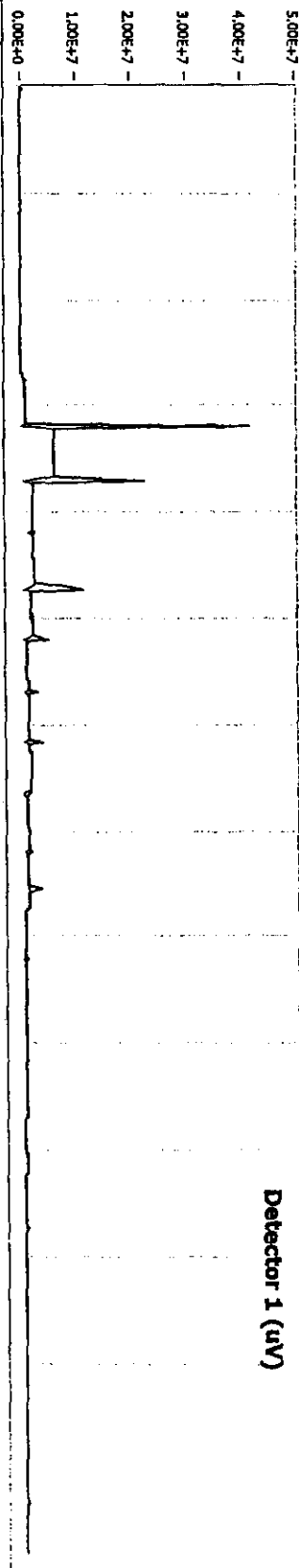


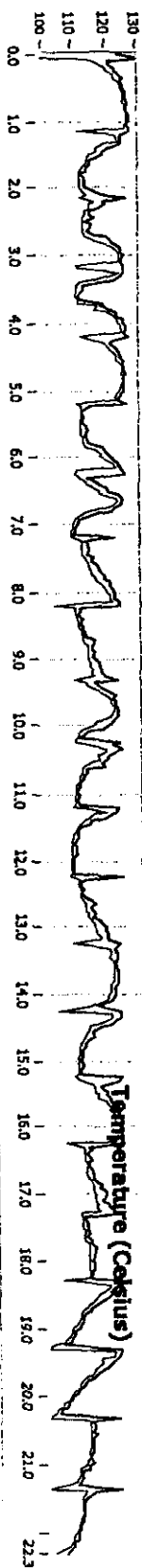
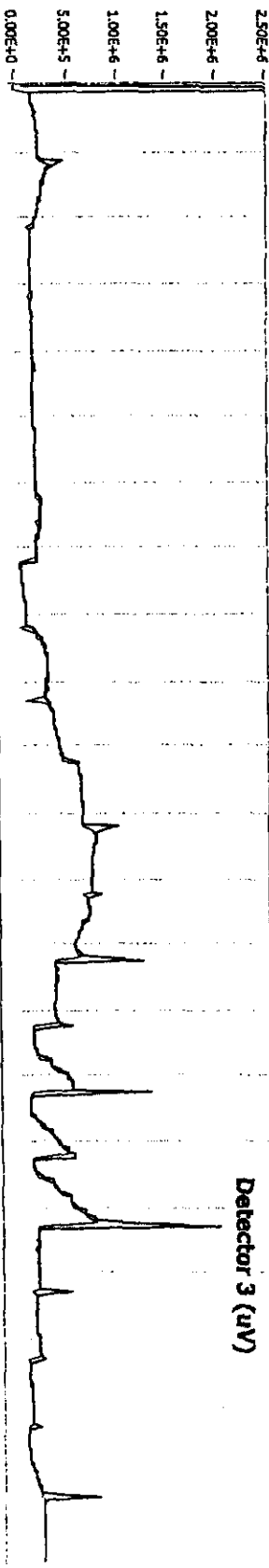
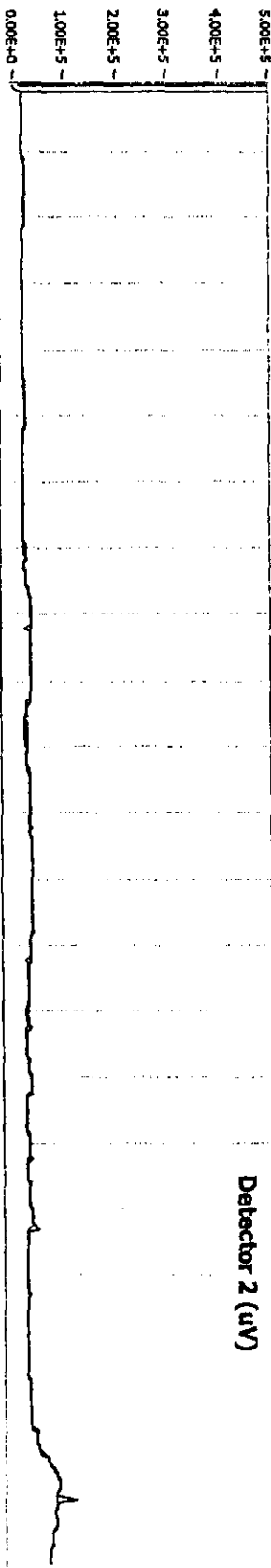
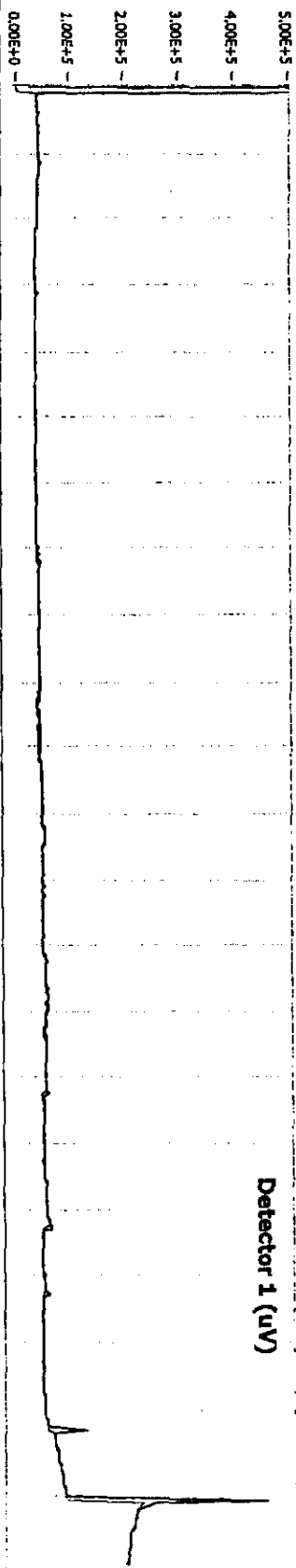
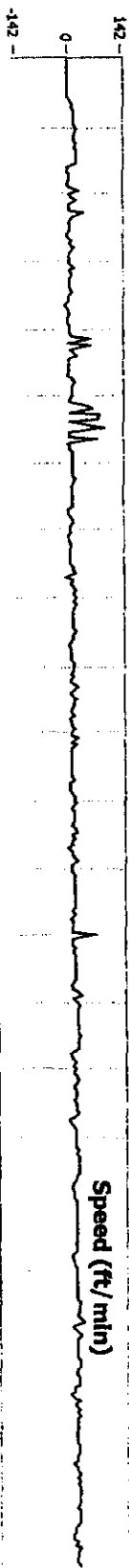
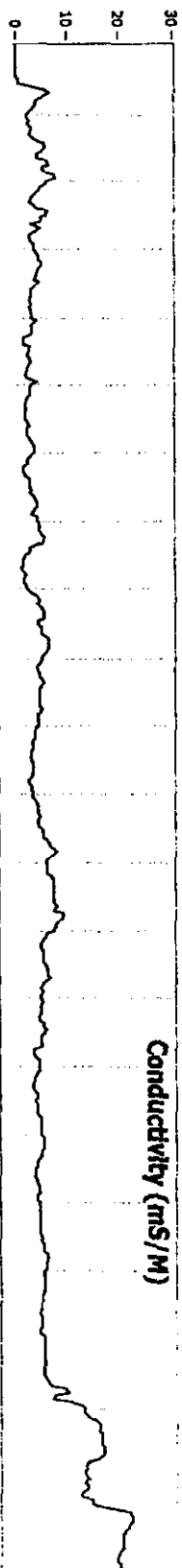


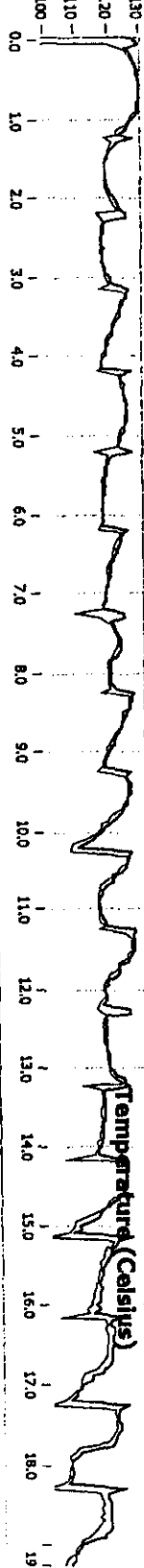
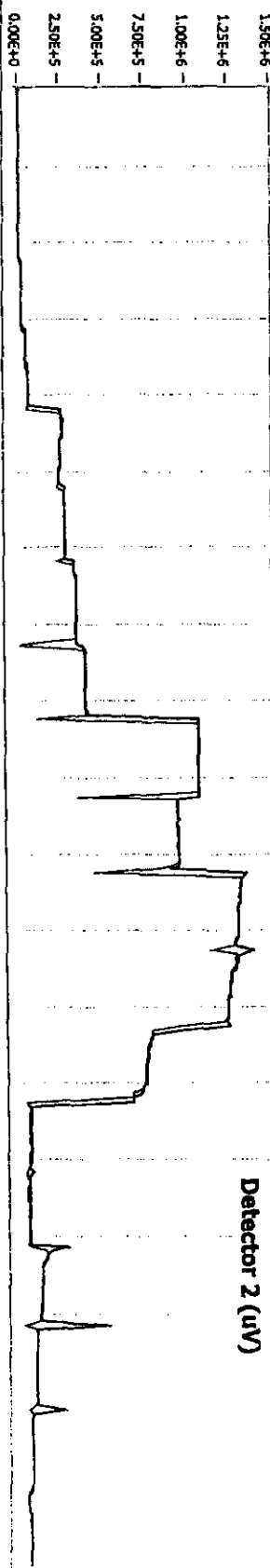
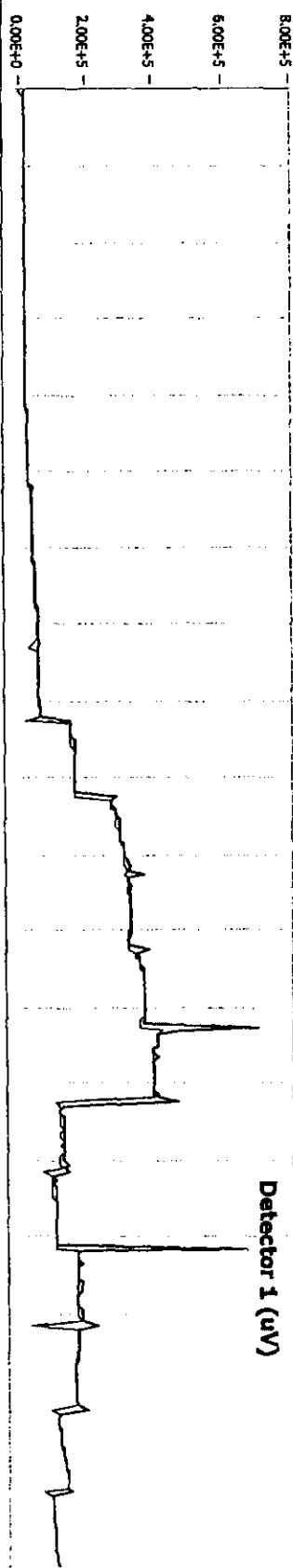
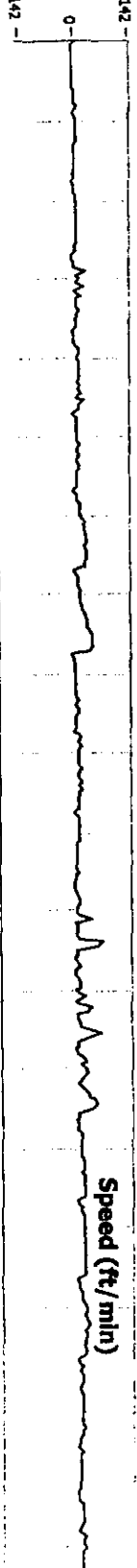
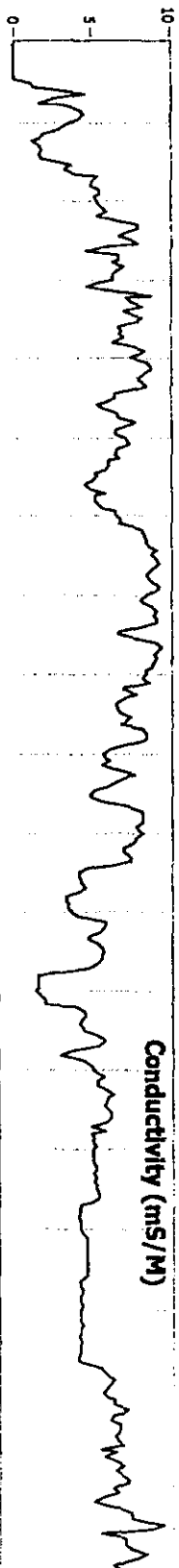


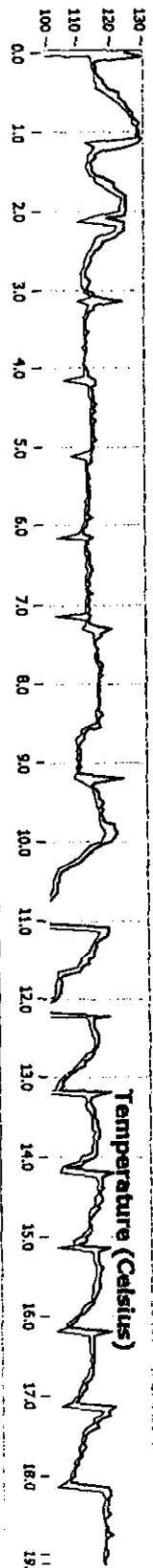
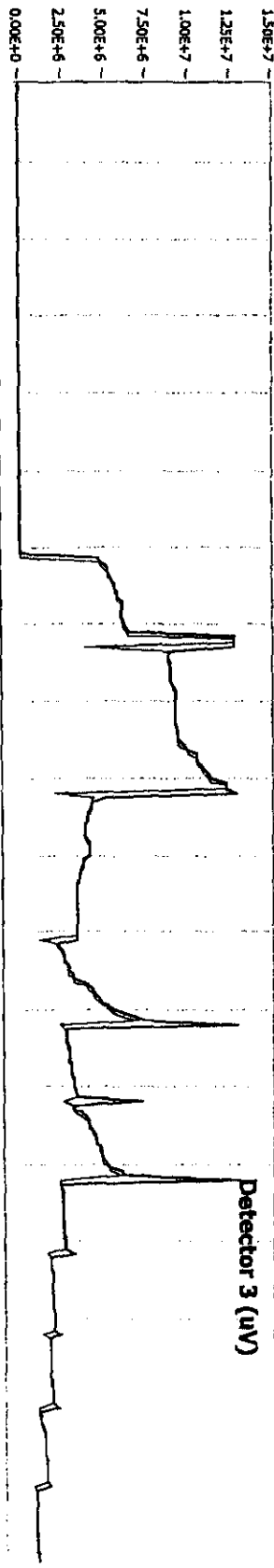
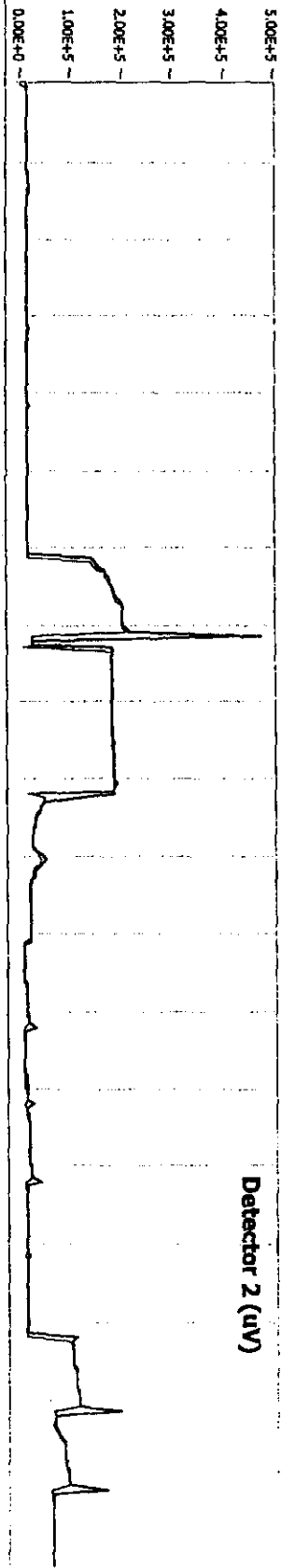
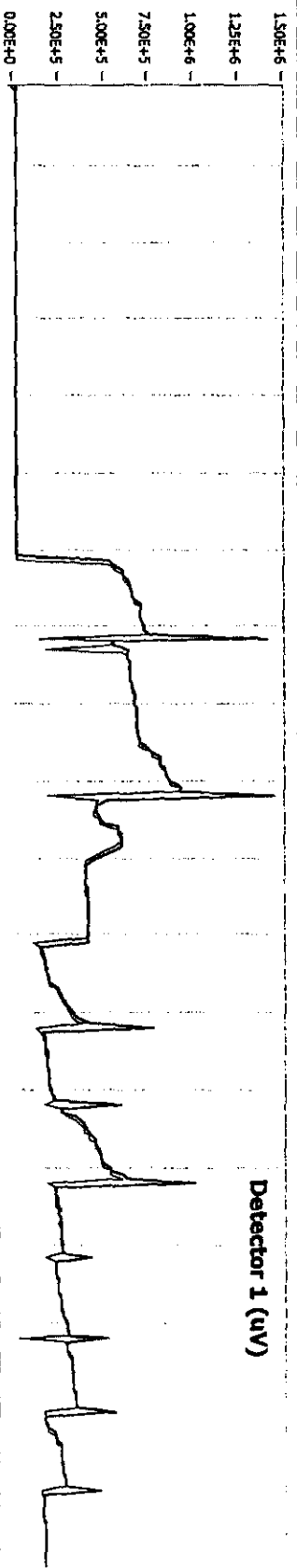
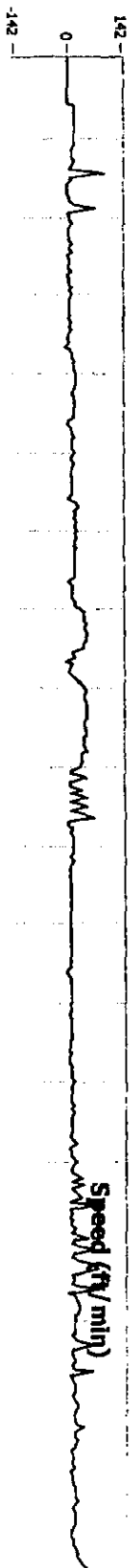
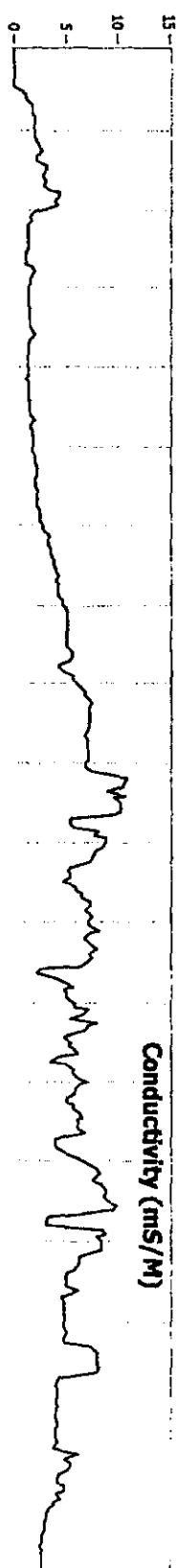












c

Appendix C
Chemical Oxidation Treatability
Study

FINAL REPORT

Maryland Sand, Gravel & Stone

Chemical Oxidation Treatability Study

June 2001

**Environmental Resources Management
Princeton Crossroad Corp. Center
250 Phillips Blvd., Suite 280
Ewing, NJ 08618**

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Environmental Resources Management's (ERM's) Remediation Technology Group (RTG) is pleased to submit this report summarizing the results of the bench scale treatability study to determine the potential effectiveness of chemical oxidation to treat the target VOCs. The treatability study was performed at ERM's Remediation Technology Center (RTC), located in West Chester, Pennsylvania. Severn-Trent Laboratories (STL) of North Canton, Ohio, the approved laboratory for the site ground water monitoring program, performed the laboratory analyses for the study.

The bench-scale treatability tests completed during the study include the following six phases of work:

Phase I: Field collection of soil and ground water samples;

Phase II: Initial characterization of soil samples;

Phase III: Determination of total soil matrix demand for potassium permanganate and sodium persulfate;

Phase IV: Determination of potassium permanganate and sodium persulfate chemical oxidation effectiveness;

Phase V: Determination of oxidant effect (potassium permanganate and sodium persulfate) on total and dissolved metals;

Phase VI: Determination of the effect of oxidation on ground water metals; and

Phase VII: Technical Memorandum.

PHASE I: FIELD COLLECTION OF SOIL AND GROUND WATER SAMPLES

Personnel from ERM performed the field sampling work to collect the representative soil and water samples to be used by ERM's RTC during the Chemical Oxidation Treatability Study. The samples were collected on March 13, 14, and 19, 2001 and stored packed in ice. Upon completion of the sampling effort, the soil and water were delivered to ERM's RTC under standard chain-of-custody procedures. The soil and water samples arrived at the RTC on March 20, 2001. After receipt by the RTC, all soil and water samples were stored refrigerated until used.

Soil samples were collected from the three major principal threat locations: the Northern Depression Area, the Buried Waste Area, and Pond 2 Wet Area. At each location, both vadose zone and saturated zone soils were obtained. The soil was collected using direct-push drilling with 2-inch diameter, thin-walled acetate sleeves (Macro-Core®, or equivalent). The soil was packed in five (5) one-liter, wide-mouth glass jars with Teflon cap liners. The expected depth to the water table was equally divided into five intervals and one jar was collected from each interval. Any non-soil material was excluded from the samples. The soil samples were handled to minimize contact with air and the jars were filled with minimal headspace. Approximately 14.9 Kg (33 pounds) of soil was collected from the Northern Depression Area on March 14; 22.3 Kg (49.1 pounds) from the Pond 2 Wet Area on March 13; and 19.5 Kg (42.9 pounds) from the Buried Waste Area on March 19, 2001.

A ground water sample was collected from well US-05 on March 14, 2001. Water from this location has historically had some of the highest concentrations of metals on the site, and this water was used to test the effect of *in situ* oxidation on metals in the ground water. Approximately twenty liters of ground water were collected without headspace in five 4-L glass bottles with Teflon lids.

All field activities followed the MSG&S Health and Safety Plan (HASP) and/or other regulatory requirements. All sample collection and laboratory studies were performed according to the site QAPP. After the testing and report is completed, all unused soil and water samples will be returned to the site.

PHASE II: INITIAL CHARACTERIZATION OF SOIL AND GROUND WATER

Prior to beginning the actual treatability experiments, the soil and ground water samples collected from the site were processed and chemically characterized as described in the sections below.

Soils: Upon arrival at the RTC, all six soil samples were placed in refrigerated storage. Chilled soil from each of the three sampling locations was then screened in a glove box containing a nitrogen atmosphere (using a 4-mm-diameter stainless-steel screen) to a uniform size to remove stones and other debris. Each screened soil was then mixed by hand to apparent homogeneity. All mixing activities were performed in the glove box to protect personnel from contact with the Contaminants of Concern (CoC) and to minimize oxidation by ambient air. Sample preparation times were kept to a minimum to avoid VOC loss during handling. These prepared soil samples were stored with minimal headspace in a refrigerator until their use in the study.

Single prepared (i.e., homogenized) soil samples from each location were shipped for overnight delivery to STL on Tuesday, March 27, 2001. The samples arrived in good condition on Wednesday, March 28, 2001. These samples were analyzed for the following parameters:

- VOCs (EPA Method 5035/8260),
- Organic Carbon Content (ASTM D-2974 and Walkley-Black protocol), and
- Chemical Oxygen Demand (COD)(ASTM D3987-85/EPA 410.4).

Ground Water: Upon arrival at the RTC, the ground water collected from well US-05 was composited and placed back into the original 4-L glass bottles. The composited ground water sample was stored refrigerated until used. The composited ground water was not analyzed prior to the study to maintain the stringent timetable for the study.

Initial Characterization Sample Results

Results of the soil sample analysis are presented in Table 1.

PHASE III: DETERMINATION OF TOTAL SOIL MATRIX OXIDANT DEMAND

Phase III evaluated the total oxidant demand (potassium permanganate and sodium persulfate, individually) of each of the six processed site

Table 1. Initial Characterization Results of Site Soils

MSG&S

7-Jun-01

1-A. Soil Analyses

Compound	NDA-08		PO-2		BWA	
	Vadose Zone mg/kg	Saturated Zone mg/kg	Vadose Zone mg/kg	Saturated Zone mg/kg	Vadose Zone mg/kg	Saturated Zone mg/kg
<i>Chloroethanes</i>						
1,1,1-Trichloroethane	300	470	0.56 J*	93	**	92
<i>Chloroethenes</i>						
Trichloroethene	140	100	1.4	120	1.4	52
Tetrachloroethene	1,600	870	9.1	280	39	170
<i>Chlorobenzenes</i>						
Chlorobenzene	4,200	1,900	16	350	66	270
<i>Aromatic Hydrocarbons</i>						
Ethylbenzene	210	110	2.1	42	10 J	33 J
Toluene	2,500	1,400	18	850	34	250
Xylenes (total)	1,400	700	13	230	77	200
<i>Non-Chlorinated Solvents</i>						
2-Butanone			1.1 J*			
4-Methyl-2-pentanone	860	360	9.8	89 J		
<i>Miscellaneous Parameters</i>						
Chemical Oxygen Demand (leachate, mg/L)	560	440	50	110	23	18 J
Total Organic Carbon	13,000	5,400	340	3,500	920	1,900

*J: Estimated result. Result is less than Reporting Limit.

** Blank indicates compound not detected at Reporting Limit

1-B. Sample Composition

Compound	NDA-08		PO-2		BWA	
	Vadose Zone %	Saturated Zone %	Vadose Zone %	Saturated Zone %	Vadose Zone %	Saturated Zone %
<i>Chloroethanes</i>	2.6	7.9	0.8	4.5	0.0	8.6
<i>Chloroethenes</i>	15.5	16.4	14.7	19.4	18.6	20.7
<i>Chlorobenzenes</i>	37.4	32.1	22.5	17.0	29.1	25.2
<i>Aromatic Hydrocarbons</i>	36.6	37.4	46.5	54.6	53.3	45.6
<i>Ketones</i>	7.6	6.1	15.3	4.3	0.0	0.0
<i>Total VOCs, mg/Kg</i>	11,210	5,910	71.1	2,054	227	1068.0
<i>Ratio of TOC to TVOC</i>	0.86	1.09	0.21	0.59	0.25	0.56
<i>Ratio of Vados to Saturated</i>	1.89		0.035		0.212	

soils (three vadose zone soils and three corresponding saturated zone soils). Total potassium permanganate or sodium persulfate oxidant demand is a function of the contaminants of concern and of other reduced species, such as iron and other soil organics (non-CoC), and these tests estimated the total mass of oxidant consumed per unit mass of the soil.

The standard oxidant demand tests were performed using soil and distilled water slurries contained in a series of 50-ml conical centrifuge tubes. Three sets of tubes were used for each of the six soil samples. One set was dosed with potassium permanganate, the other two sets with sodium persulfate. For each set, 25 grams of wet-weight processed soil was added to each of ten 50-mL centrifuge tubes. An appropriate volume of a stock potassium permanganate or sodium persulfate solution was then added to each tube, followed by distilled water to bring the total liquid volume in each tube to approximately 40 mL. The ten tubes make up an oxidant mass series ranging from 1 to 500 mg of potassium permanganate or 2.5 to 1,250 mg of sodium persulfate per tube; each tube in a series contains twice the concentration of the preceding tube.

Additional permanganate oxidant demand tests were performed with increased permanganate levels. These additional tests were performed only on the North Depression Area samples from both the saturated and unsaturated zones. One set of eight tubes was prepared for each of the samples. For each set, 25 grams of wet weight processed soil was added to each of the eight 50-mL centrifuge tubes. An appropriate volume of a stock solution of sodium permanganate was then added to each tube, followed by distilled water to bring the total liquid volume in each tube to approximately 40 mL. The eight tubes make up a mass series ranging from 1,000 to 8,000 mg of sodium permanganate per tube.

Standard Permanganate Demand Tests

All permanganate-treated centrifuge tubes for the standard demand test were prepared on March 27, 2001 and mixed by hand periodically over a 7-day reaction period. Upon completion of the 7-day reaction period on April 3, 2001, each tube was centrifuged to produce distinct soil and aqueous phases. The Oxidation-Reduction Potential (ORP) of the aqueous layer was measured and recorded. The color of the aqueous phase in each tube was visually determined and recorded. Solutions containing residual permanganate were pink to purple in color, while solutions in which the starting mass of permanganate has been essentially exhausted will be colorless.

The data from this experiment is provided in Tables 2.

Standard Persulfate Demand Tests

All of the persulfate treated centrifuge tubes for the standard demand test were prepared on March 28, 2001 and mixed by hand periodically over the required reaction period. Upon completion of the 7-day reaction period on April 4, 2001, one set of tubes for each sample was centrifuged to produce distinct soil and aqueous phases. The ORP of each liquid fraction was measured and recorded. The approximate concentration of unreacted persulfate in each liquid fraction was also determined by titration with ferrous sulfate using a starch iodide indicator. At the conclusion of the 21-day reaction period on April 18, 2001, the remaining persulfate treated tubes were processed and tested in the same manner as the 7-day persulfate treated tubes.

The data from this experiment is provided in Table 2.

Additional Permanganate Demand Tests with Increased Levels

The two sets of tubes for the additional permanganate demand tests were prepared on April 10, 2001 and mixed periodically over a 7-day reaction period. At the conclusion of the 7-day reaction period on April 17, 2001, each tube was centrifuged to produce distinct soil and aqueous phases. The ORP of the aqueous layer was measured and recorded. The color of the aqueous phase in each tube was visually determined and recorded.

2.4

PHASE IV: DETERMINATION OF CHEMICAL OXIDATION EFFECTIVENESS

This phase of the Treatability Study evaluated the effectiveness of potassium permanganate, sodium persulfate, and various combinations of these oxidants as treatment alternatives for the oxidation of the VOCs present in the MSG&S samples. The conditions evaluated included (1) potassium permanganate alone, (2) sodium persulfate with ferrous iron alone, (3) a combination of permanganate and persulfate with ferric iron, and (4) sequential permanganate-persulfate. The chemical oxidation effectiveness for each of the reaction conditions was evaluated over a 38-day reaction period, with the exception of a 39-day reaction period for the permanganate only aqueous phase and an additional permanganate only soil. All of the VOC analyses were performed according to the current CLP Statement of Work.

Table 2. Results of Permanganate and Persulfate Total Oxidant Demand Tests

MSG&S
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2A									
Oxidant	NDA-08		PO-2		BWA-23				
	Vadose Zone g/kg wet weight	Saturated Zone g/kg wet weight	Vadose Zone g/kg wet weight	Saturated Zone g/kg wet weight	Vadose Zone g/kg wet weight	Saturated Zone g/kg wet weight			
Potassium Permanganate (7 Day)	40 to 80	20 to 40	2.3 to 4.6	9.7 to 20	2.3 to 4.7	2.2 to 4.7			
Sodium Persulfate (7 Day)	0.35 to 0.71	0.71 to 1.41	< 0.09	2.8 to 5.7	< 0.09	0.18 to 0.35			
Sodium Persulfate (21 Day)	0.71 to 1.41	0.09 to 0.18	< 0.09	1.41 to 2.8	< 0.09	0.18 to 0.35			

2B									
Oxidant	NDA-08		PO-2		BWA-23				
	Vadose Zone	Saturated Zone	Vadose Zone	Saturated Zone	Vadose Zone	Saturated Zone			
Measured TOC, mg/kg	13,000	5,400	340	3,500	920	1,900			
Total COC, mg/kg	11,210	5,910	71.1	2,054	227	1068.0			
Calculated Non-COC TOC, mg/kg	5662	1733	291	2115	759	1236			
Permanganate Demand from TOC	g/kg wet weight	g/kg wet weight	g/kg wet weight	g/kg wet weight	g/kg wet weight	g/kg wet weight			
Permanganate Stoichiometric Demand	20-60	9-18	1-3	12-20	5-9	7-12			
	165	82	1	31	3	14			
Persulfate Demand from TOC	40-70	16-30	2-6	19-30	8-15	10-18			
Persulfate Stoichiometric Demand	373	185	3	71	8	32			

The soil used with these studies was a 1:1:1 composite of soil from the Northern Depression Area vadose zone, the Buried Waste Area saturated zone, and Pond 2 Wet Area saturated zone. The composited soil was prepared in a glove box containing a nitrogen atmosphere, where the soils were mixed by hand to apparent homogeneity. The soils used for the composited sample were selected on the basis of their high oxidant demands exhibited in the soil demand tests in Phase III of the Treatability Study. The theoretical concentration of each VOC present in the composited soil was calculated using the VOC concentrations determined for each soil in the Initial Characterization tests. The composited soil was also spiked so that the soil utilized in the test would contain the CoCs at concentrations observed within the Principal Threat areas. Table 3 provides the average of the native concentrations of the CoCs in the composited soil, the amount of each CoC added, and the final concentration achieved for the oxidation efficiency tests.

The slurry experiments were conducted in glass screw-cap centrifuge bottles. These bottles contained a working volume of approximately 210 mL. The composited soil (prepared from the three site locations) was mixed with distilled water containing the oxidants to form a slurry containing 20% solids by weight. The spike solution of CoCs was added directly to the soil in the centrifuge tube, just before the addition of the distilled water with the oxidants. Three such bottles were constructed for each of the five test conditions.

The amount of oxidant added to each of the bottles was based upon the Phase III Total Oxidant Demand test results and the total theoretical oxidant demand from the VOC mass spiked into each slurry. The estimated total oxidant mass needed was the sum of the soil oxidant demand and the spiked VOC oxidant mass demand. A one and one-half fold excess of this total amount of oxidant was mixed with the required volume of distilled water and then added to the soil spiked with VOCs in the centrifuge bottle.

Similar centrifuge bottles without added permanganate and/or persulfate were also prepared as experimental controls for the experiment. These controls were used to determine whether volatile losses occur during the test procedure, and if so, whether the losses are a significant issue. In addition to the two control bottles prepared for the experiment, a similar centrifuge bottle was also constructed and used at the beginning of the experiment to provide starting soil and aqueous contaminant concentrations for the experiment.

One bottle from each test condition was analyzed after 38 days of treatment. This analysis determined which contaminants react quickly

Table 3. Concentration Levels of the Composited Soil for Phase IV Oxidation-Efficiency Test.

MSG&S

7-Jun-01

Compound	Native Concentration of CoCs in Soil Composite* mg/kg	Spiked CoC Concentration in Soil Composite mg/kg	Final CoC Concentration in Soil Composite mg/kg
Benzene	ND	990	990
Methylene Chloride	ND	970	970
Tetrachloroethene	600	1,000	1,600
Trichloroethene	90	990	1,080
Vinyl Chloride	ND	20	20
Chlorobenzene	1,400	1,000	2,400
Chloroethane	ND	200	200
1,2 Dichloroethane	ND	990	990
1,1-Dichloroethene	ND	1,000	1,000
cis-1,2-Dichloroethene	ND	1,000	1,000
Acetone	ND	980	980
2-Butanone	280	990	1,270

*This represents the average concentration based upon the initial characterization results and a 1:1:1 composite of soils NDA-08 (unsaturated), PO2 (saturated), and BWA (saturated).

All concentrations presented in this table are on a wet-weight basis, with the CoC spikes added to 42 grams of soil.

ND = Not Detected.

with the different oxidants. Two additional bottles were also prepared to potentially determine whether a longer reaction period is needed to oxidize previously difficult to treat compounds such as methylene chloride, 1,2-dichloroethane, and chloroethane.

Permanganate Only Treatment: On April 13, 2001, a 121 g/L mixture of potassium permanganate in distilled water was prepared and added to three centrifuge tubes containing 42 grams of composited soil spiked to the desired level with CoCs. The bottles were sealed immediately and allowed to incubate at room temperature with periodic mixing.

On May 21, 2001, the 38th day of reaction, the slurry in one bottle was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers and cooled. The pH and ORP of a separate portion of slurry was also measured. The sample containers were then packaged in ice and shipped for overnight delivery to STL for a duplicate analysis for VOCs. These samples arrived at STL in good condition on May 22, 2001, but the sample log-in personnel at the laboratory dropped the sample containers for the aqueous fraction during the unpacking of the containers resulting in breakage of all sample bottles provided for this fraction. The laboratory notified RTC personnel of this problem during a follow-up phone call May 22, 2001 to confirm the condition of the samples upon receipt at the laboratory. On May 22, the slurry in one of the other Permanganate Only Treatment bottles was processed in the same manner as the previous bottle, and the soil and water fraction were shipped for overnight delivery to STL for a duplicate analysis for VOCs. These sample arrived at STL in good condition on May 23, 2001.

Data from the analysis of these samples is provided in Table 4.

Persulfate Plus Ferrous Iron Only Treatment: On April 13, 2001, a solution containing 260 g/L of sodium persulfate and 500 mg/L ferrous iron in distilled water was prepared and added to three centrifuge tubes containing 42 grams of composited soil spiked to the desired level with CoCs. The bottles were sealed immediately and allowed to incubate at room temperature with periodic mixing.

On May 21, 2001, the 38th day of reaction, the slurry in one bottle was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers and cooled. The pH and ORP of a separate portion of slurry was also measured. The sample containers were then packaged in ice and shipped for overnight delivery to STL for a duplicate analysis for VOCs. These samples arrived at STL in good condition on May 22, 2001.

Table 4a. Oxidation Efficiency Test Raw Data

MSG&S

7-Jun-01

Compound	Time = 0 Control				Time = Final Control				Time = Final Persulfate + Iron				Time = Final Combined				Time = Final Sequential			
	Water (mg/L)		Soil (mg/kg)		Water (mg/L)		Soil (mg/kg)		Water (mg/L)		Soil (mg/kg)		Water (mg/L)		Soil (mg/kg)		Water (mg/L)		Soil (mg/kg)	
	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2
<i>Chlorinated</i>																				
Chloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Methylene chloride	180	190	59	23	160	170	34	33	140	140	87	92	94	110	96	86	95	95	57	62
Chloroform	2.4	2.4	ND	ND	1.3	1.5	ND	ND	1.3	1.3	ND	ND	ND	1	ND	ND	ND	ND	ND	ND
<i>Chlorinated</i>																				
Chloroethane	30	33	ND	ND	31	33	ND	ND	18	18	ND	ND	17	17	10	12	11	12	6	ND
1,1-Dichloroethane	130	140	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-Dichloroethane	150	170	150	53	160	160	61	60	150	150	150	160	220	230	130	150	100	120	120	110
1,1,1-Trichloroethane	11	11	97	36	9.3	8.4	25	25	7.9	8.2	69	75	7.1	7.5	65	73	6.1	8.3	3.1	19
1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.2	3.5	8.4	9.6	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.6	1.8	13	14	ND	ND	ND	ND
<i>Chlorinated</i>																				
Vinyl Chloride	3.3	3.6	ND	ND	2.7	3.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethene	ND	ND	120	34	110	120	93	92	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-Dichloroethene (total)	150	170	150	53	160	150	90	90	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Trichloroethene	74	81	560	270	73	68	230	230	ND	ND	ND	63	ND	ND	27	26	ND	ND	ND	ND
Tetrachloroethene	33	38	1,300	760	30	29	530	530	ND	ND	80	85	2.4	2.6	480	570	ND	ND	47	55
<i>Chlorobenzenes</i>																				
Chlorobenzene	89	95	2,000	1,000	95	93	650	650	100	100	1,600	1,700	2.1	ND	430	480	47	60	1,700	650
<i>Aromatic Hydrocarbons</i>																				
Benzene	110	110	320	130	120	110	140	140	92	96	310	340	ND	ND	17	19	32	41	270	90
Toluene	50	53	800	380	54	53	260	260	7.2	7.2	240	250	ND	ND	78	90	ND	ND	120	35
Ethylbenzene	1.6	1.7	75	43	1.6	1.7	28	28	ND	ND	ND	ND	ND	ND	21	23	ND	ND	ND	ND
Xylenes (total)	10	12	470	270	11	11	180	180	ND	ND	210	230	ND	ND	120	130	ND	ND	140	30
<i>Non-Chlorinated Solvents</i>																				
Acetone	140	160	ND	26	79	78	ND	15	2.3	1.8	ND	ND	20	22	ND	ND	78	87	29	ND
4-Methyl-2-pentanone	180	180	110	62	190	170	41	40	3.4	3.4	ND	ND	ND	ND	2.2	2.2	1.7	2.2	ND	ND

J: Estimated result. Result is less than Reporting Limit.

B: Compound detected in corresponding method blank.

ND - Not Detected above reporting limit.

Results in bold are below the Principal Threat cleanup criteria

Table 4b. Oxidation Efficiency Test Raw Data

MSG&S

7-Jan-01

Compound mass/volume (kg/L) percent solid	Time = 0 Control				Time = Final Control				Time = Final Permanganate				Time = Final Persulfate + Iron				Time = Final Combined				Time = Final Sequential			
	Water (mg)		Soil (mg)		Water (mg)		Soil (mg)		Water (mg)		Soil (mg)		Water (mg)		Soil (mg)		Water (mg)		Soil (mg)		Water (mg)		Soil (mg)	
	0.207	Dup 1	0.207	Dup 2	0.207	Dup 1	0.042	Dup 2	0.207	Dup 1	0.042	Dup 2	0.207	Dup 1	0.042	Dup 2	0.207	Dup 1	0.042	Dup 2	0.207	Dup 1	0.042	Dup 2
Chloromethanes																								
Chloromethane	37.3	39.3	2.5	1.0	33.1	35.2	1.0	1.0	29.0	29.0	2.2	2.3	26.9	26.9	2.0	2.3	19.5	22.8	2.7	2.4	19.7	19.7	1.7	1.8
Methylene chloride	0.5	0.5			0.3	0.3			0.3	0.3			0.6	0.6				0.2						
Chloroform																								
Chloroethanes																								
Chloroethane	6.2	6.8			6.4	6.8			3.7	3.7			3.5	3.5	0.3	0.3	2.3	2.5			1.2	1.2		
1,1-Dichloroethane	26.9	29.0			33.1	33.1	1.9	1.8	31.1	31.1	3.8	4.0	24.8	26.9	3.5	4.1	20.7	24.8	5.3	4.8	24.8	24.8	3.2	3.2
1,2-Dichloroethane	31.1	35.2	6.3	2.2	33.1	33.1	1.9	1.7	1.7	1.7	1.9	1.9	1.5	1.6	1.8	2.0	1.3	1.7	2.5	2.5	0.7	0.6	0.6	0.6
1,1,1-Trichloroethane	2.3	2.3	4.1	1.5	1.9	1.7	0.8	0.8	1.6	1.7			0.7	0.7	0.2	0.3								
1,1,2-Trichloroethane													0.3	0.4	0.4	0.4								
1,1,2,2-Tetrachloroethane																								
Chloroethenes																								
Vinyl Chloride	0.7	0.7			0.6	0.7																		
1,1-Dichloroethene			5.0	1.4	24.8	24.8	2.8	2.8																
1,2-Dichloroethene (total)	31.1	35.2	6.3	2.2	33.1	33.1	2.7	2.7																
Trichloroethene	15.3	16.8	23.5	11.3	15.1	14.1	7.0	7.0							1.7				0.8	0.7				
Tetrachloroethene	6.8	7.9	54.6	31.9	6.2	6.0	16.1	16.1			2.0	2.1	0.5	0.5	13.0	15.4			1.9	1.9			1.4	1.6
Chlorobenzenes																								
Chlorobenzene	18.4	19.7	84.8	42.0	19.7	19.3	19.8	19.8			40.1	42.6	0.4		11.6	13.0			47.8	47.8	5.6	5.4	16.2	19.2
Aromatic Hydrocarbons																								
Benzene	22.8	22.8	13.4	5.5	24.8	22.8	4.3	4.3																
Toluene	10.4	11.0	33.6	16.0	11.2	11.0	7.9	7.9	1.5	1.5	6.0	6.3			0.5	0.5	6.6	8.5	7.6	7.9	3.5	3.3	2.3	2.7
Ethylbenzene	0.3	0.4	3.2	1.8	0.3	0.4	0.9	0.9							2.1	2.4			3.4	3.4			0.9	1.0
Xylenes (total)	2.1	2.5	19.7	11.3	2.3	2.3	5.5	5.5			5.3	5.8			3.2	3.5			3.9	3.9			0.7	0.9
Non-Chlorinated Solvents																								
Acetone	29.0	33.1		1.1	16.4	16.1		0.5	0.5	0.4			4.1	4.6			16.1	18.0	1.0	0.8	2.3	2.3		
4-Methyl-2-pentanone	37.3	37.3	4.6	2.6	39.3	35.2	1.2	1.2	0.7	0.7							0.4	0.5						

Table 4c. Oxidation Efficiency Test Total Mass Data

MSG&S

7-jun-01

Compound	Time = 0 Control		Time = Final Control		Time = Final Permanganate		Time = Final Persulfate + Iron		Time = Final Combined		Time = Final Sequential	
	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2	Dup 1	Dup 2
<i>Chloromethanes</i>												
Chloromethane							0.5	0.5				
Methylene chloride	39.7	40.3	34.2	35.2	31.2	31.3	28.9	29.2	22.2	25.2	21.3	21.5
Chloroform	0.5	0.5	0.3	0.3	0.3	0.3	0.6	0.8		0.2		
<i>Chloroethanes</i>												
Chloroethane	6.2	6.8	6.4	6.8	3.7	3.7	3.8	3.8	2.3	2.5	1.2	1.2
1,1-Dichloroethane	26.9	29.0										
1,2-Dichloroethane	37.4	37.4	35.0	34.9	34.8	35.1	28.4	31.0	26.0	29.6	28.1	28.1
1,1,1-Trichloroethane	6.4	3.8	2.7	2.5	3.4	3.6	3.2	3.5	3.7	4.2	1.2	1.3
1,1,2-Trichloroethane							0.9	1.0				
1,1,2,2-Tetrachloroethane							0.7	0.8				
<i>Chloroethylenes</i>												
Vinyl Chloride	0.7	0.7	0.6	0.7								
1,1-Dichloroethene	5.0	1.4	25.6	27.6								
1,2-Dichloroethene (total)	37.4	37.4	35.9	33.8								
Trichloroethene	38.8	28.1	22.1	21.1			1.7		0.8	0.7		
Tetrachloroethene	61.4	39.8	22.3	21.1	2.0	2.1	13.5	15.9	1.9	1.9	1.4	1.6
<i>Chlorobenzenes</i>												
Chlorobenzene	102.4	61.7	39.4	39.0	60.8	63.3	12.0	13.0	57.6	60.3	21.8	24.5
<i>Aromatic Hydrocarbons</i>												
Benzene	36.2	28.2	29.1	27.0	26.8	28.4	0.5	0.5	14.2	16.4	5.8	6.0
Toluene	44.0	26.9	19.1	18.9	7.5	7.8	2.1	2.4	3.4	3.4	0.9	1.0
Ethylbenzene	3.5	2.2	1.2	1.2			0.6	0.6				
Xylenes (total)	21.8	13.8	7.8	7.8	5.3	5.8	3.2	3.5	3.9	3.9	0.7	0.9
<i>Non-Chlorinated Solvents</i>												
Acetone	29.0	34.2	16.4	16.6	0.5	0.4	4.1	4.6	17.2	18.8	2.3	2.3
4-Methyl-2-pentanone	41.9	39.9	40.6	36.4	0.7				0.4	0.5		

Table 4d. Oxidation Efficiency Test Average Mass

MSG&S

7-jun-01

Compound	Time = 0 Control mg	Time = Final Control mg	Time = Final Permanganate mg	Time = Final Persulfate + Iron mg	Time = Final Combined mg	Time = Final Sequential mg
<i>Chloromethanes</i>						
Chloromethane				0.507		
Methylene chloride	40.0	35.2	31.2	29.0	23.7	21.4
Chloroform	0.50	0.29	0.269	0.724		
<i>Chloroethanes</i>						
Chloroethane	6.5	6.6	3.73	3.82	2.38	1.20
1,1-Dichloroethane	27.9					
1,2-Dichloroethane	37.4	35.0	34.9	29.7	27.8	28.1
1,1,1-Trichloroethane	5.07	2.59	3.47	3.37	3.98	1.27
1,1,2-Trichloroethane				0.937		
1,1,2,2-Tetrachloroethane				0.716		
<i>Chloroethenes</i>						
Vinyl Chloride	0.71	0.61				
1,1-Dichloroethene	3.23	26.6				
1,2-Dichloroethene (total)	37.4	34.8				
Trichloroethene	33.5	21.6		1.70	0.746	
Tetrachloroethene	50.6	22.2	2.07	14.7	1.89	1.50
<i>Chlorobenzenes</i>						
Chlorobenzene	82.0	39.2	62.1	12.5	58.9	23.2
<i>Aromatic Hydrocarbons</i>						
Benzene	32.2	28.1	27.6	0.486	15.3	5.88
Toluene	35.4	19.0	7.63	2.27	3.38	0.96
Ethylbenzene	2.82	1.19		0.594		
Xylenes (total)	17.8	7.75	5.52	3.38	3.94	0.811
<i>Non-Chlorinated Solvents</i>						
Acetone	31.6	16.5	0.424	4.35	18.0	2.28
4-Methyl-2-pentanone	40.9	38.5	0.704		0.404	

Table 4e. Percent Reduction

MSG&S

7-111-01

Compound	Percent Reduction (vs. T=0)	Percent Reduction (vs. Control)			
	Control	Potassium Permanganate	Potassium Persulfate + Iron	Combined	Sequential
Chloromethanes					
Chloromethane	NA	NA	NA	NA	NA
Methylene chloride	12.1%	11.2%	17.4%	32.7%	39.1%
Chloroform	41.7%	7.1%	-149.9%	100.0%	100.0%
Chloroethanes					
Chloroethane	-1.6%	43.8%	42.4%	64.1%	81.9%
1,1-Dichloroethane	100.0%	NA	NA	NA	NA
1,2-Dichloroethane	6.5%	0.066%	15.2%	20.4%	19.7%
1,1,1-Trichloroethane	48.9%	-33.930%	-30.2%	-53.6%	51.1%
1,1,2-Trichloroethane	NA	NA	NA	NA	NA
1,1,2,2-Tetrachloroethane	NA	NA	NA	NA	NA
Chloroethenes					
Vinyl Chloride	14.5%	100.0%	100.0%	100.0%	100.0%
1,1-Dichloroethene	-723.1%	100.0%	100.0%	100.0%	100.0%
1,2-Dichloroethene (total)	6.9%	100.0%	100.0%	100.0%	100.0%
Trichloroethene	35.5%	100.0%	92.1%	96.5%	100.0%
Tetrachloroethene	56.1%	90.7%	33.9%	91.5%	93.2%
Chlorobenzenes					
Chlorobenzene	52.2%	-58.3%	68.1%	-50.2%	40.9%
Aromatic Hydrocarbons					
Benzene	12.9%	1.6%	98.3%	45.5%	79.1%
Toluene	46.4%	59.8%	88.0%	82.2%	95.0%
Ethylbenzene	57.7%	100.0%	50.2%	100.0%	100.0%
Xylenes (total)	56.5%	28.8%	56.4%	49.2%	89.5%
Non-Chlorinated Solvents					
Acetone	47.8%	97.4%	73.6%	-9.2%	86.2%
4-Methyl-2-pentanone	5.8%	98.2%	100.0%	99.0%	100.0%

Data from the analysis of these samples is provided in Table 4.

Combined Permanganate & Persulfate Treatment: On April 13, 2001, a solution of 130 g/L of sodium persulfate, 60 g/L of potassium permanganate, and 1 g/L of ferric iron in distilled water was added to three centrifuge tubes containing 42 grams of composited soil spiked to the desired level with CoCs. The bottles were sealed immediately and allowed to incubate at room temperature with periodic mixing.

On May 21, 2001, the 38th day of reaction, the slurry in one bottle was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers and cooled. The pH and ORP of a separate portion of slurry was also measured. The sample containers were then packaged in ice and shipped for overnight delivery to STL for a duplicate analysis for VOCs. These samples arrived at STL in good condition on May 22, 2001.

Data from the duplicate analysis of these samples is presented in Table 4.

Sequential Permanganate & Persulfate Treatment: On April 13, 2001, a 121 g/L mixture of potassium permanganate in distilled water was added to three centrifuge tubes containing 42 grams of composited soil spiked to the desired level with CoCs. The bottles were sealed immediately and allowed to incubate for nineteen days with periodic mixing. On May 3, 2001, the 21st day of treatment, sufficient solid ferrous sulfate (approximately 2 grams) was added to the contents of one centrifuge tube to reduce the excess permanganate remaining in the bottle. This endpoint was evidenced by the loss in purple color of the liquid contents of the bottle. Following complete reduction of the permanganate, 42 grams of sodium persulfate was added to the centrifuge tube. This bottle was then sealed and allowed to continue reacting for the completion of the 38-day period.

On May 21, 2001, the 38th day of reaction, the slurry in the bottle treated with the additional sodium persulfate was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers and cooled. The pH and ORP of a separate portion of slurry was also measured. The sample containers were then packaged in ice and shipped for overnight delivery to STL for a duplicate analysis for VOCs. These samples arrived at STL in good condition on May 22, 2001.

Data from the duplicate analysis of these samples is present in Table 4.

Time-Zero and Control Samples: On April 13, 2001, distilled water was added to four centrifuge tubes containing 42 grams of composited soil

spiked to the desired level with CoCs. All of the bottles were sealed immediately. Three of these bottles were identified as control samples, and they were allowed to incubate at room temperature with periodic mixing. The remaining bottle was identified as the "Time = 0" sample. This bottle was continuously shaken for a 2-hour period in order to allow contaminant equilibration between the soil and water phases. At the conclusion of this 2-hour period, the slurry in the "Time = 0" bottle was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers and cooled. Readings for the pH and ORP of the "Time = 0" sample were obtained from an identical "Time = 0" sample prepared for Phase V of the project. The sample containers were then packaged in ice on April 13 and shipped for overnight delivery to STL for a duplicate analysis for VOCs. The samples were delivered to the laboratory on Monday, April 16, 2001 instead of Saturday, April 14, 2001. The laboratory indicated that these samples arrived out of temperature (at 11 degrees Celsius rather than 4 degrees Celsius as required). A decision was made by ERM to proceed with these samples in order to meet the project schedule and to consider the data generated provisional.

On May 21, 2001, the 38th day of incubation, the slurry in one of the Control bottles was centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers, and cooled. The pH and ORP of a separate portion of slurry was also measured. The sample containers were then packaged in ice and shipped for overnight delivery to STL for a duplicate analysis for VOCs. These samples arrived at STL in good condition on May 22, 2001.

Data from the duplicate analysis of the "Time = 0" and Control samples is presented in Table 4.

2.5

PHASE V: DETERMINATION OF OXIDANT EFFECT ON TOTAL AND DISSOLVED METALS

This phase of the Treatability Study evaluated the effects of permanganate and persulfate treatment on the concentration of total and dissolved metals found in the aqueous fraction of a soil slurry. The five slurry treatment conditions investigated in Phase IV were repeated in this experiment, but the set-up of the individual sample bottles was modified to produce the volume of water required by the analytical laboratory to achieve the specified metals detection limits. Loss of VOCs in this experiment was expected, but was inconsequential to the goal of the tests.

The treatment conditions that were evaluated were: (1) potassium permanganate alone; (2) sodium persulfate with ferrous iron alone; (3) a combination of permanganate and persulfate with ferric iron; (4) sequential permanganate-persulfate; and (5) control (no oxidants added). The experiments were set-up in 1.5-liter capped bottles, with two bottles prepared for each condition. Each bottles contained a 20% by weight slurry of composited soil (prepared as described in Phase IV) distilled water. The composited soil was spiked with the same proportional concentration of VOC CoCs and carrier solvent used in the Phase IV work, with the exception of chloroethane and vinyl chloride. These two compounds were omitted due to the cost of spiking the larger amount of soil used in this phase of the study. In addition to these test conditions, a "Time = 0" sample was prepared to establish the concentration of the metals of concern at the beginning of the experiment.

The analytes of concern for this phase of the project were total and dissolved arsenic, manganese, iron, chromium, hexavalent chromium, and mercury. The arsenic, iron, manganese, mercury, and chromium analyses were performed by US EPA SOW ILMO4.1 procedures. The analysis for hexavalent chromium was performed by US EPA SW-846 Procedure 7196A. The filtration for the dissolved metals was performed at the laboratory.

Permanganate Only Treatment: On April 24, 2001, two permanganate only treatment bottles were prepared by combining 300 grams of composited soil spiked with VOC CoCs, 1200 mL of distilled water, and 143 grams of potassium permanganate in each bottle. The initial pH and ORP of the slurry was measured and recorded. The bottles were then closed, incubated at room temperature, and mixed by hand twice daily Monday through Friday.

On May 20, 2001, the 26th day of reaction, the pH and ORP of the slurries in the two bottles were measured and recorded. The pH of one of the pair of bottles was adjusted to 7, and the contents of this bottle were mixed thoroughly. On May 21, 2001, the aqueous phase of each bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The bottle adjusted to pH 7 was labeled as Perman-1 while the remaining bottle was labeled as Perman-2. The sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on May 22, 2001.

Data from the metals analysis of these samples is presented in Table 5.

Table 5. Effect of Oxidants on Dissolved and Total Metals.

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5-A. pH Adjusted Prior to Analysis

Analyte	Condition	Control (T = 0)		Control (T = Final)		Permanganate ug/L	Persulfate + Iron ug/L	Combined Dup 1 ug/L	Sequential ug/L
		Dup 1 ug/L	Dup 2 ug/L	Dup 1 ug/L	Dup 2 ug/L				
Arsenic	Total	4.0 J*	7.8 J	4.1 B		3.1 B	ND	ND	ND
	Dissolved	2.0 J	ND	ND		6.2 B	ND	ND	ND
Chromium	Total	18.7	95.5	18.7		1,590	247	10,700	47.7 B
	Dissolved	2.9 J	3.2	9 B		2,920	202	10,500	98.9
Chromium (VI)	Total	20 J	ND	ND		MI***	180	MI	20
	Dissolved	ND	ND	ND		MI	100	MI	ND
Iron	Total	2,040	13,800	4,230		ND	2,020	2,620	7,570
	Dissolved	201	160	1,230		ND	681	ND	ND
Manganese	Total	80.7	99.7	62.2 E		185 E	475 E	48,200 E	9,250 E
	Dissolved	75.9	86.2	36.5 E		431 E	723 E	86,800 E	137 E
Mercury	Total	0.73	1.2	0.34		0.4	0.36	2.2	19
	Dissolved	ND	3.2	0.21		0.27	0.39	1.9	25

*J: Estimated result. Result is less than Reporting Limit.

** Blank space indicates that analyte was not detected above Reporting Limit

***MI: Matrix interference

5-B. pH Unadjusted Prior to Analysis

Analyte	Condition	Control (Time = 0)		Control (T = Final)		Permanganate ug/L	Persulfate + Iron ug/L	Combined ug/L	Sequential ug/L
		Dup 1 ug/L	Dup 2 ug/L	Dup 1 ug/L	Dup 2 ug/L				
Arsenic	Total	4.0 J*	7.8 J	2.2 B		21.1	50	ND	83.3 B
	Dissolved	2.0 J	ND	2.9 B		5.5 B	51.5	ND	97.5 B
Chromium	Total	18.7	95.5	17.4		158	7,990	5,400	1,850
	Dissolved	2.9 J	3.2	16.2		1,040	8,040	5,230	2,040
Chromium (VI)	Total	20 J	ND	ND		MI	50	MI	MI
	Dissolved	ND	ND	ND		MI	60	MI	MI
Iron	Total	2,040	13,800	827		ND	549,000	603	2,450,000
	Dissolved	201	160	122		ND	553,000	ND	2,710,000
Manganese	Total	80.7	99.7	209 E		1,500,000 E	1,830 E	28,700 E	8,380,000 E
	Dissolved	75.9	86.2	482 E		371,000 E	2,700 E	285,000 E	9,760,000 E
Mercury	Total	0.73	1.2	0.22		0.30	4.9	1.1	25.9
	Dissolved	ND	3.2	0.29		0.16 B	4.8	0.79	27.4

*J: Estimated result. Result is less than Reporting Limit.

** Blank space indicates that analyte was not detected above Reporting Limit

***MI: Matrix interference

Persulfate Plus Iron Only Treatment: On April 24, 2001, two persulfate plus iron only treatment bottles were prepared by combining 300 grams of soil spiked with VOC CoCs, 1200 mL of distilled water, 314 grams of sodium persulfate, and 3 grams of ferrous sulfate in each bottle. The initial pH and ORP of the slurry was measured and recorded. The bottles were then closed, incubated at room temperature, and mixed by hand twice daily Monday through Friday.

On May 20, 2001, the 26th day of reaction, the pH and ORP of the slurries in the two bottles were measured and recorded. The pH of one of the pair of bottles was adjusted to 7, and the contents of this bottle were mixed thoroughly. On May 21, 2001, the aqueous phase of each bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The bottle adjusted to pH 7 was labeled as Persul-1 while the remaining bottle was labeled as Persul-2. The sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on May 22, 2001.

Data from the metals analysis of these samples is presented in Table 5.

Combined Permanganate & Persulfate Treatment: On April 24, 2001, two combined treatment bottles were prepared by combining 300 grams of composited soil spiked with VOC CoCs, 1200 mL of distilled water, 72 grams of potassium permanganate, 157 grams of sodium persulfate, and 3.5 grams of ferric chloride. The initial pH and ORP of the slurry was measured and recorded. The bottles were then closed, incubated at room temperature, and mixed by hand twice daily Monday through Friday.

On May 20, 2001, the 26th day of reaction, the pH and ORP of the slurries in the two bottles were measured and recorded. The pH of one of the pair of bottles was adjusted to 7, and the contents of this bottle were mixed thoroughly. On May 21, 2001, the aqueous phase of each bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The bottle adjusted to pH 7 was labeled as Comb-1 while the remaining bottle was labeled as Comb-2. The sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on May 22, 2001.

Data from the metals analysis of these samples is presented in Table 5.

Sequential Permanganate & Persulfate Treatment: On April 24, 2001, two sequential treatment bottles were prepared by combining 300 grams of composited soil spiked with VOC CoCs, 1200 mL of distilled water, and 143 grams of potassium permanganate in each bottle. The initial pH and ORP of each bottle was measured and recorded. The bottles were then closed, incubated at room temperature, and mixed by hand twice daily Monday through Friday.

On May 9, 2001, ferrous iron (in the form of ferrous sulfate) was added to each of the bottles. Over 400 milliequivalents was added to each of the bottles, but this amount was not enough to reduce the excess permanganate remaining in the bottle after only a nine day incubation period. An additional 600 milliequivalents (added as ferrous ammonium sulfate to) added to the bottle identified as Seq-2 was still not sufficient to reduce the remaining permanganate. A spectrophotometric determination of the permanganate remaining in both of the bottles indicated that an excessive amount of ferrous iron would be required to complete the reduction of the permanganate. Based on this information, sodium metabisulfite, a compound that reduces permanganate at approximately a 1:1 ratio (on a gram:gram basis), was selected as an appropriate alternative for reducing the remaining permanganate in the two bottles. On May 15, 2001, a calculated excess of sodium metabisulfite was added to each of the bottles and the contents were allowed to react overnight. On the following day, the contents of bottle labeled as Seq-1 had no residual permanganate color. The contents of the bottle labeled as Seq-2 appeared to have some purple color remaining, so some additional sodium metabisulfite was added until there was no evidence of the permanganate. The pH of each of the bottles was less than 2.5 at this point, so sodium hydroxide was added to bring the pH to 7. This was followed by the addition of 314 grams of sodium persulfate to each bottle to complete the sequential treatment.

On May 20, 2001, the 26th day of reaction, the pH and ORP of the slurries in the two bottles were measured and recorded. The pH of the bottle labeled as Seq-1 was adjusted to 7, and the contents of this bottle were mixed thoroughly. On May 21, 2001, the aqueous layer of each bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on May 22, 2001.

Data from the metals analysis of these samples is presented in Table 5.

Time-Zero and Control Samples: On April 24, 2001, three bottles were prepared by combining 300 grams of composited soil spiked with VOC CoCs and 1200 mL of distilled water. The initial pH and ORP of the slurries were measured and recorded. Two of the bottles, identified as "Control Samples", were closed, incubated at room temperature, and mixed by hand twice daily Monday through Friday for the entire reaction period. The remaining bottle, identified as the "Time = 0" sample, was mechanically mixed for a 2 hour period on April 24. At the conclusion of the two hour mixing period, the aqueous layer of this bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The sample containers were packaged in ice and shipped for overnight delivery to STL for a duplicate analysis of metals of concern. This "Time = 0" sample arrived at STL in good condition on April 25, 2001.

On May 20, 2001, the 26th day of reaction, the pH and ORP of the slurries in the two bottles were measured and recorded. The pH of one of the pair of bottles was adjusted to 7, and the contents of this bottle were mixed thoroughly. On May 21, 2001, the aqueous of each bottle was decanted into a centrifuge tube. The contents were centrifuged and the remaining aqueous layer transferred to the appropriate sample containers. The bottle adjusted to pH 7 was labeled as Control-1 while the remaining bottle was labeled as Control-2. The sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on May 22, 2001.

Data from the metals analysis of these samples is presented in Table 5.

Confirmation of Initial pH and ORP Readings for Phase V Conditions: Unusually low pH readings were obtained with the initial measurements performed for the bottles on April 24, 2001. On May 23, 2001, another set of each reaction condition was prepared to confirm these initial measurements. These bottles were prepared with 10-fold less composited soil, distilled water and oxidants added to each bottle. The contents of the bottles were mixed by hand and the pH measured for each slurry.

The following were the pH values:

Bottle	pH	ORP
Control-1	4.54	345
Control-2	4.61	341
Permanganate-1	8.84	620
Permanganate-2	8.90	610

Persulfate-1	1.19	840
Persulfate-2	1.16	833
Combined-1	7.31	664
Combined-2	6.72	733
Sequential-1	2.83	886
Sequential-2	2.67	893

2.6 PHASE VI: EFFECT OF OXIDATION ON SOLUBLE METALS

Phase VI of the Treatability Study was designed to evaluate the change in solubility of dissolved metals in the presence of the chemical oxidants. It is expected that the oxidation reaction would decrease dissolved concentrations of each of the metals of concern since most metals are more soluble in a reduced state or significantly less soluble in the oxidized state. During *in situ* chemical oxidation iron is converted from ferrous (Fe^{+2}) to the less soluble ferric (Fe^{+3}), arsenic from arsenite (AsO_2^-) to the less soluble arsenate (AsO_4^{3-}), and manganese from manganous (Mn^{+2}) to the less soluble manganese dioxide (MnO_2). The Phase VI experiments were designed to demonstrate this decrease in dissolved metals concentrations with the site ground water sample obtained from well US-05.

This study utilized a Control sample, a permanganate treated sample and a persulfate treated sample, as described below. The analytes of concern for this phase of the project were total and dissolved arsenic, manganese, iron, chromium, hexavalent chromium, and mercury. The arsenic, iron, manganese, mercury, and chromium analyses were performed by US EPA SOW ILMO4.1 procedures. The analysis for hexavalent chromium was performed by US EPA SW-846 Procedure 7196A. The filtration for the dissolved metals was performed at the laboratory.

Control: On April 17, 2001, two liters of ground water sample US-05 was transferred to a reaction flask and equilibrated to room temperature. After equilibration, the pH and ORP of the ground water was measured and recorded. The amount of ground water required for the metals analysis was transferred to the appropriate sample containers and cooled. On April 18, 2001, the sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on April 19, 2001.

Results for the metals analysis of these samples are presented in Table 6.

Permanganate-Treated: On April 17, 2001, a four liter aliquot of ground water sample US-05 was transferred to a reaction flask and equilibrated to room temperature. After equilibration, the pH and ORP of the ground water was measured and recorded. Potassium permanganate was added gradually to the ground water with constant stirring and measurement of ORP. Addition of the permanganate was continued until the ORP fell within the range of 600 to 700 mv. A total of 10 grams of the potassium permanganate was added to the 4-liter aliquot to achieve this ORP level. The permanganate treated ground water was then stirred continuously for one hour followed by another measurement of pH and ORP.

The experimental design called for the treated ground water to be divided into two equal fractions at this stage, followed by the neutralization of one fraction to a pH of 7. However, the pH reading for the treated ground water at this point of the experiment was already at a pH of 7, so the neutralization step was not required and the entire aliquot of treated ground water was handled as one sample. The volume of ground water required for the metals analysis was transferred to the appropriate sample containers and cooled. On April 18, 2001, the sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on April 19, 2001.

Data from the metals analysis of these samples are presented in Table 6.

Persulfate-Treated: On April 17, 2001, a four liter aliquot of ground water sample US-05 was transferred to a reaction flask and equilibrated to room temperature. After equilibration, the pH and ORP of the ground water was measured and recorded. Sodium persulfate was added gradually to the ground water with constant stirring and measurement of ORP. Addition of the persulfate was continued until the ORP fell within the range of 600 to 700 mv. A total of 663 grams of the sodium persulfate was added to the 4-liter aliquot to achieve this ORP level. The persulfate treated ground water was then stirred continuously for one hour followed by another measurement of pH and ORP.

The experimental design called for the treated ground water to be divided into two equal fractions at this stage, followed by the neutralization of one fraction to a pH of 7. However, the pH reading for the treated ground water at this point of the experiment was already at a pH of 7, so the neutralization step was not required and the entire aliquot of treated ground water was handled as one sample. The volume of ground water required for the metals analysis was transferred to the

Table 6. Phase VI Results

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Compound	US-05					
	Control		Permanganate		Persulfate	
	Total ug/L	Dissolved ug/L	Total ug/L	Dissolved ug/L	Total ug/L	Dissolved ug/L
Arsenic	6.2 J	5.0 J	5.3 J	6.0 J	26.5	2.7 J
Chromium	25.9	15.8	48.3	46.2	28.3	1.9 J
Iron	52,800	16,800	8,900		50,000	61.5 J
Potassium						
Magnesium						
Manganese	56.3	54.7	289,000	273,000	61.8	28.1
Mercury	1.7	0.60	0.19	1.2		
Chromium (VI)	0.01 J	0.01 J				

*J: Estimated result. Result is less than Reporting Limit.
blank indicates compound not detected at Reporting Limit

appropriate sample containers and cooled. On April 18, 2001, the sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on April 19, 2001.

A technical review of the experiment on April 19 concluded that the amount of persulfate required to generate this sample was excessive, and a modified persulfate treatment study was initiated. The laboratory was notified on April 19, 2001 that the analysis of the persulfate treated sample received on that day was not required.

Persulfate-Treated (Revised): On April 19, 2001, a 4-liter aliquot of ground water sample US-05 was transferred to a reaction flask and equilibrated to room temperature. After equilibration, the pH and ORP of the ground water was measured and recorded. Ten grams of sodium persulfate was added to the ground water in a covered container. Measurements of the solution pH and ORP were taken just after the addition of the oxidant and following a ten to fifteen minute reaction period with mixing. This process was repeated until a stable ORP was obtained. Once the ORP reached apparent stability, the solution was allowed to equilibrate for an additional 70 minutes to confirm the ORP stability. The entire process required the addition of a total of 30 grams of sodium persulfate to achieve a stable ORP reading of 410 mv.

The experimental design called for the treated ground water to be divided into two equal fractions at this stage, followed by the neutralization of one fraction to a pH of 7. However, the pH reading for the treated ground water at this point of the experiment was already at a pH of 7, so the neutralization step was not required and the entire aliquot of treated ground water was handled as one sample. The volume of ground water required for the metals analysis was transferred to the appropriate sample containers and cooled. On April 19, 2001, the sample containers were packaged in ice and shipped for overnight delivery to STL for the analysis of metals of concern. These samples arrived at STL in good condition on April 20, 2001.

3.0 DISCUSSION OF RESULTS

3.1 INITIAL CHARACTERIZATION

The initial characterization results for the three sampling locations are shown in Table 1. Each location had a vadose zone and saturated zone sample. Table 1A shows the results for the individual CoCs. Table 1B gives the results as the percent composition. Several general observations can be made of the three soil sample locations.

The Northern Depression samples (NDA-08) were the most contaminated. The contaminants in this area were primarily chlorobenzene and aromatic hydrocarbons. The bulk of the contamination was also located in the vadose zone.

The Pond 2 samples (PO-2) were the next most contaminated. The vadose zone sample in the Pond 2 area was, however, very lightly contaminated. The contaminants of concern were primarily aromatic hydrocarbons, comprising almost 50% of the CoCs. Chlorobenzene and the chloroethenes were the next most prevalent at about 20% each. Most of the contamination in the Pond 2 area is in the saturated zone.

The Buried Waste Area samples (BWA) were the least contaminated. Aromatic hydrocarbons were roughly 50% of the CoCs. Chlorobenzene was the next highest COC at 25%. Chlorinated ethenes were present at 20% of the total. The bulk of the CoCs were located in the saturated zone.

In all of the three areas the primary CoCs are readily oxidizable. The chlorinated ethenes and the aromatic hydrocarbons can be oxidized by both permanganate and persulfate. Chlorobenzene, however, can only be oxidized by persulfate.

3.2 SOIL DEMAND

A critical factor to determine in assessing the applicability of in situ chemical oxidation is to determine the amount of oxidant that is required. The oxidant demand is a function of two factors, the amount of contaminants present and the presence of other, non-specific oxidizable species such as reduced metals and naturally occurring organics. ERM has developed a protocol for assessing the soil demand for both

permanganate and persulfate. This procedure measures the total soil demand. If the total soil demand is much greater than the theoretical stoichiometric demand for oxidation of the COCs, then it is likely that the soil has a high amount of reactive materials, which may consume oxidant and compete with the oxidation of the contaminants of concern.

Table 2 gives the results for the soil demand tests. Included in Table 2A are a 7-day permanganate demand and a 7 and 21-day persulfate demand test. The demand tests were run on each of the soil samples. Included in Table 2B are a calculated stoichiometric demand based on the initial characterization results for the soil samples and a soil demand based on the TOC values for the sample. The TOC values in Table 2B were adjusted for the CoCs present in the sample.

In general, the permanganate soil demand values were much higher than the persulfate soil demand values. This is consistent with ERM's general observations of soil demand values in other chemical oxidation studies. It appears that persulfate does not readily react with naturally occurring organics. Persulfate also reacts more slowly with contaminants than does permanganate. As a result, the soil demand values for persulfate are significantly lower than those for permanganate.

The permanganate demand values for the soil samples varied from moderate to very high. The northern depression area soils had very high permanganate demand values. The Pond 2, saturated zone sample, had the next highest permanganate demand. All the other samples had only moderate demands.

The soil demand for permanganate can be accounted for by the CoCs present or by the TOC value. There appears to be a very strong correlation between the soil demand and concentration of CoCs and the TOC values. The three highest soil demand values, 40-80, 20-40, and 9.7-20 had corresponding VOC concentrations of 11,200 mg/kg; 5,910 mg/kg; and 2054 mg/kg; and TOC values of 13,000 mg/kg; 5,400 mg/kg; and 3,500 mg/kg. It is difficult to differentiate between the TOC and CoCs. Both will obviously consume oxidant.

At the TOC/COC levels present in the soil samples from the northern depression area, in situ chemical oxidation would be very expensive. A soil demand of 80 g/kg equates to about 200 lbs. of permanganate per yd³ of soil. This represents a cost of approximately \$300/yd³ just for the permanganate alone.

The economics for persulfate use in the northern depression area are equally poor. Although the soil demand for persulfate is much lower

than that for permanganate, the potential stoichiometric demand would equate to more than 500 Lbs. of persulfate per yd³ of soil, at a cost of more than \$500 per yd³ for the persulfate alone.

3.3

OXIDATION EFFICIENCY TESTING

Four separate oxidation tests were run. They included permanganate alone, persulfate alone, combined permanganate/persulfate, and sequential permanganate/persulfate. The results are presented in Table 4. A control was run along with the four oxidation tests.

The most accurate way to assess the results of the oxidation efficiency testing is to examine the total mass of CoCs in the different experimental runs. The amount of water and soil used in each experiment varied. Also the partitioning of the CoCs between the soil and water phase would also vary. Using the total mass normalizes the results and allows for comparisons between experiments.

Table 4 presents the oxidation efficiency test data in several different formats. Table 4a presents the raw concentration data. All samples were run in duplicate. Table 4b presents the concentration data converted to mass data; results are given for both soil and water. Table 4c provides the total sum, adding together the mass in the soil and the mass in the water. The results are given for both duplicates. Table 4d provides the average mass data for each experiment. In Tables 4a-4d, a blank signifies that that compound was not detected above the reporting limit. Table 4e converts the mass data into the percent reduction. The percent reduction is calculated between the T=0 and T=final control to show any losses due to handling. The percent reduction for the individual experiments is calculated relative to the control (T=Final) to compensate for the volatile losses. There was an approximate 35% loss in VOCs in the control T=Final (based on the 12 highest mass VOCs- see below)

It should be noted that there are several VOCs present in these experiments that were not detected in the initial characterization. Of particular note are benzene, methylene chloride, and 1,2- and 1,1-dichloroethane. These were added to the composite soil (See Table 3).

The CoCs present in these experiments in order of decreasing mass were:

Chlorobenzene	82.0
Tetrachloroethene	50.6
4-Methyl-2-pentanone	40.9
Methylene chloride	40.0
1,2-Dichloroethane	37.4
1,2-Dichloroethene (total)	37.4
Toluene	35.4
Trichloroethene	33.5
Benzene	32.2
Acetone	31.6
1,1-Dichloroethane	27.9
Xylenes (total)	17.8
Chloroethane	6.5
1,1,1-Trichloroethane	5.07
1,1-Dichloroethene	3.23
Ethylbenzene	2.82
Vinyl Chloride	0.71
Chloroform	0.50

The oxidation of the top 12 CoCs (Chlorobenzene to Xylene) will be discussed below.

Chlorobenzene was partially oxidized by persulfate and by sequential permanganate/persulfate. It was not oxidized at all by permanganate. The best result was for persulfate alone, resulting in a 68% reduction relative to the control. The sequential permanganate/persulfate treatment resulted in a 40% reduction relative to the control. It should be noted, however, that the persulfate alone treatment was conducted for 38 days, while the persulfate phase of the sequential treatment lasted only 18 days.

Tetrachloroethene (PCE) was reduced by more than 90% relative to the control by permanganate, combined permanganate and persulfate, and

sequential permanganate/persulfate. It was only reduced 34% relative to the control by persulfate alone. Based on these results, it may be concluded that in the combined and sequential oxidation studies, most of the PCE reduction was due to the permanganate. In other experiments, ERM has seen the complete destruction of PCE with both permanganate and persulfate. It may be concluded, therefore, that the incomplete reduction of PCE is due to competitive interference; the oxidants react more readily with other CoCs. As the oxidant is consumed its concentration decreases and the kinetics slow.

4-Methyl-2-pentanone (MIBK) is completely removed by persulfate and by sequential permanganate persulfate. It is reduced by > 98% by permanganate and combined permanganate/persulfate.

Methylene Chloride is only partially oxidized. The best results were for combined and sequential permanganate/persulfate, a 32 and 39% reduction. The results for permanganate or persulfate alone were 11 and 17%. Methylene chloride is very slow to oxidize.

1,2-Dichloroethane is also only partially oxidized. It responds only to the oxidant systems containing persulfate. Permanganate has no effect on the 1,2-dichloroethane. The combined and sequential permanganate and persulfate gave the best results with a 20% reduction. This compares to a 15% reduction with persulfate alone.

1,2-Dichloroethene (total) was completely oxidized by all systems. The carbon-carbon double bond increases the reactivity of the dichloroethene.

Toluene is significantly oxidized by all the oxidant systems. The systems containing persulfate showed a greater reduction than permanganate alone. The best results, 95%, reduction were obtained with the sequential permanganate and persulfate. Persulfate seems to be effective against aromatics. While permanganate alone did not completely remove toluene (60% reduction), other studies by ERM have shown the complete destruction of toluene with permanganate in as short of a time frame as used in this study. The reaction with toluene may have been affected by the preferential reaction of the permanganate with other CoCs.

Trichloroethene (TCE) was substantially oxidized by all systems. The permanganate alone and the sequential permanganate/persulfate completely removed the TCE. The persulfate alone and the combined permanganate/persulfate showed a 92% and 97% reduction. Permanganate appears to be more reactive to chlorinated ethenes than is persulfate. However, both oxidants are effective.

Benzene does not react with permanganate but is effectively oxidized by persulfate. Persulfate alone showed a 98% reduction of benzene. The sequential permanganate/persulfate had a 80% reduction.

Acetone reacted best with permanganate (97% reduction). Sequential permanganate/persulfate had a 86% reduction. Persulfate alone had a 74% reduction. The combined permanganate and persulfate showed no reaction. This may have been an aberrant result as acetone reacts with both oxidants.

1,1-Dichloroethane was only found in the T=0 control. Since it was not present in the T=Final control, it is not possible to determine if it is oxidized.

Xylenes (total) respond as do the other aromatics. The best results were obtained with the systems containing persulfate. The sequential permanganate - persulfate gave the best results (89.5% reduction).

There are several general conclusions that can be drawn from these experiments. First of all, there is a rough order of reactivity. The chlorinated ethenes react first, followed by the substituted aromatic hydrocarbons (TEX), followed by benzene/chlorobenzene. The chloromethanes and chloroethanes react very slowly. Second, permanganate has more reactivity limitations than does persulfate. It will not react with benzene, chlorobenzene, chloromethanes or chloroethanes. Third, using both oxidants gave the best results. The best overall system appeared to be the sequential use of permanganate/persulfate; the second best system was the combined permanganate/persulfate. Neither oxidant by itself was as effective over the full range of CoCs as the dual-oxidant systems. Fourth, it is expected that better results will be obtained with longer reaction times, especially for the chlorinated ethanes and methanes.

3.4 EFFECT ON METALS

Two experiments were run to determine the effect of the oxidants on metal solubilization. The first experiment was run with soil slurries. The second set of experiments was run on ground water alone. The results are shown in Tables 5 and 6.

In the slurry experiments the bottles were analyzed with and without pH adjustment. In all analyses the water was analyzed both filtered and unfiltered. This provides data to differentiate between metals which are particulate in nature and metals which are dissolved.

Table 5 provides the data for the slurry study. Several conclusions may be drawn from this data. First of all, most of the elevated metals in the samples are due to shifts in the pH or due to formation of particulates. In general, adjusting the pH to neutral and filtering reduced the metals. The metals that are most affected by the oxidation are iron, manganese and chromium. Persulfate has the greatest effect on iron, primarily due to the production of acid during reaction. Permanganate has the greatest effect on manganese for an obvious reason. Permanganate also has the greatest effect on chromium. Persulfate does not seem to react very quickly with chromium. Table 6 provides the data for the ground water study. As can be seen from the data, the addition of an oxidant generally reduces the dissolved metals. The high manganese in the permanganate treated sample is unreacted permanganate. Most of the metals after the addition of an oxidant are in particulate form.

The conclusion of the metal study is that the most critical factor is the pH. Some of the reactions will produce acid. Neutralization after treatment reduces the metal levels.

CONCLUSION

The treatability study has demonstrated the efficacy of chemical oxidation. All of the CoCs were oxidized in part or in whole. However, the study identified several factors that would make the application of *in situ* chemical oxidation complex.

First of all, a single oxidant does not perform as well as a combination of oxidants. This is because there is a complex mixture of contaminants, which react at different rates with the two oxidants. It appears from the results of the study that sequential permanganate/persulfate treatment gave the best performance.

Second, some areas of the site, particularly the northern depression area, have soil demand and COC levels that make chemical oxidation economically questionable. The cost of chemicals alone could be \$200-300/yd³ for permanganate and over \$500/yd³ for persulfate, if used alone.

Third, the application of oxidants at high levels can result in a pH shift due to the production of acid. This can result in the solubilization of some metals from the soil. Adjusting the pH mitigates the solubilization. This was demonstrated both with the slurry tests and the tests with groundwater. The Phase VI samples were pH adjusted. The dissolved metal levels were low.

D

Appendix D
Chemical Oxidation Treatability
Testing – 70-Day Tests

4 September 2001
Reference: 48410.22.01

Mr. Doug Ammon
Clean Sites Environmental Services, Inc.
228 S. Washington Street, Suite 115
Alexandria, VA 22314



Re: Maryland Sand Gravel & Stone, Elkton, MD
Chemical Oxidation Treatability Testing - 70-day Tests

Dear Doug:

This letter discusses the results obtained from the optional Phase IV in-situ chemical oxidation treatability samples run at ERM's remediation Technology Center (RTC) laboratory in Exton, PA. The results of the 38-day laboratory treatability test were presented in ERM's Remediation Technology Screening Technical Memorandum, dated June 14, 2001. Additional samples from the same initial batch startup for the 38-day tests (i.e., T=0) were allowed to react with the tested oxidants for an additional 32 days, thus resulting in a 70-day test period. The test cells and procedures were identical to those used in the 38-day tests, as documented in the Technical Memorandum. The tested samples were allowed to react at room temperature for a total of 70 days, in order to compare the results with those previously reported in the base study using a reaction time of 38 days. In addition, results are presented for process development testing using heated persulfate (Attachment A) that indicate potentially significant implications with respect to the potential for combining the in-situ thermal and chemical oxidation technologies at the Maryland Sand Gravel and Stone Site (MSG&S).

70-day Chemical Oxidation Results

The 70-day tests are a supplement to the 38-day tests; results of which were reported in the Technical Memorandum. The additional testing was performed in an effort to assess the effect of additional oxidant contact time with the baseline VOC levels in the tested media (i.e., soil slurries) with respect to oxidation efficiency. The tested media samples were established at the baseline time (T=0) that was used for the original 38-day tests. You may recall that the initial samples for the 38-day tests (and the 70-day tests) were established using representative

maximum concentrations of the primary constituents (i.e. volatile organic compounds [VOCs]) of concern from the MSG&S site, and at a minimum, the constituents found to represent a Ground Water Principal Threat as defined in the Focused Feasibility Study, Interim Final (ERM, July 2001).

The 70-day treatment conditions evaluated included:

- potassium permanganate alone;
- sodium persulfate with ferrous iron alone;
- a combination of permanganate and persulfate with ferric iron; and
- sequential permanganate-persulfate. [These tests were run for 49 days using potassium permanganate, followed by 21 days with an addition of sodium persulfate.]

The optional 70-day samples for each condition and appropriate controls were constructed at the same time (i.e., T=0) as the base study samples on 13 April 2001. The optional 70-day samples were handled in the following manner:

- On 1 June 2001, the bottles for the "potassium permanganate only" condition and the "combined permanganate-persulfate" condition were treated with additional potassium permanganate since the original permanganate added to these slurries was exhausted, as indicated by the lack of purple permanganate color in these bottles. The amount of permanganate added to each bottle was one-half the original amount of permanganate added on 13 April 2001;
- Addition of the persulfate and ferrous iron to the "sequential permanganate-persulfate" bottle was performed on 1 June 2001; and
- On 1 June 2001, the bottles for the "persulfate only" condition and the "Control" were opened for approximately the same period of time that the other three treatment conditions were opened in

order to compensate for any volatile losses incurred through the additional handling procedures.

All optional 70-day bottles were incubated at room temperature with periodic mixing Monday through Friday. On 22 June 2001, the slurries in all of the bottles were centrifuged into distinct soil and aqueous fractions, transferred to the appropriate sample containers, and cooled. The individual soil and aqueous fraction samples were then packaged in ice and shipped for overnight delivery to the designated laboratory, STL-Dayton, OH, for VOC analyses in accordance with proper chain of custody procedures, and consistent with procedures followed for the 38-day tests.

Table 1 presents the raw data for the soil and aqueous fractions of each slurry. The average "Time = 0" soil and water results from the base study are provided for comparison purposes. In order to better compare the effectiveness of treatment under the four test conditions, the raw data in Table 1 were used to calculate the total mass (i.e., sum of the soil and aqueous fractions) of each specific contaminant present in each reaction bottle, as shown in Table 2. The effectiveness of treatment was calculated as a percent reduction in the total mass (soil and aqueous fraction) of each constituent relative to its average initial total mass (sum of soil and aqueous fraction) in the "Time=Final" (i.e., T=Final) control samples. The calculated percent reductions for each constituent under each treatment condition are presented in Table 3. Table 3 also shows the reduction in each contaminant mass vs. its starting mass ("Time = 0", or T=0) for the "Time = Final" (i.e., T=Final) controls samples as an indicator of losses that may have occurred during the test, and with respect to the "Time = Final" mass for each treatment condition as an indicator of the removal effectiveness for each treatment condition.

For the chloromethanes, methylene chloride was removed to a greater degree with persulfate treatment. Of the chloromethanes present, 30% to 45% of the mass of methylene chloride was removed when treated with persulfate (either alone, in combination with permanganate, or sequentially with permanganate); permanganate alone was ineffective in reducing methylene chloride mass. The additional duration seemed to significantly improve the results for persulfate with iron, but had no additional effect on the combined or sequential tests. With respect to the treatment of chloroform, the apparent loss in the control, coupled with the high analytical variability, preclude commenting on the effectiveness

of treatment. Because of this ambiguity, it is prudent to conclude that neither oxidant was effective in treating chloroform.

For the chloroethanes, persulfate treatment (alone, in combination, and sequentially) reduced the mass of chloroethane by 77% to 96%, while permanganate produced only a 15% reduction. For 1,2-dichloroethane, persulfate treatment (alone, in combination, and sequentially) achieved a mass reduction of 15% to 48%, compared with no reduction using permanganate. For 1,1,1-trichloroethane, analytical variability was high, and moderate mass reductions (approximately 60% to 65%) were only observed with combined and sequential treatment. No comment can be made about the effectiveness of treatment for 1,1-dichloroethane since the compound was not detected in the "Time Final" control.

For the chloroethenes, persulfate and permanganate appear to be equally effective (95% to 100%) in treating vinyl chloride, 1,1-dichloroethene, 1,2-dichloroethene (total), and trichloroethene. The tetrachloroethene data showed essentially complete treatment using permanganate and combined permanganate and persulfate. Treatment of this compound using persulfate with iron showed a moderate reduction of 55%. Sequential treatment showed a 90% reduction in contaminant mass.

Permanganate treatment produced a modest (38%) reduction in chlorobenzene mass. The combined and sequential use of permanganate and persulfate yielded moderate removals of 63% to 66%. Persulfate with iron treatment resulted in the greatest degree of removal (76%). It should be noted that chlorobenzene was completely removed from the aqueous phase in the 70-day persulfate sample, and that the remaining chlorobenzene mass in this sample was present only in the soil fraction. This is consistent with previous technology development work by RTC staff which has shown that various chlorobenzenes (in ground water or spiked into distilled water) can be successfully treated with persulfate (with iron) at room temperature. The favorable aqueous persulfate treatment results at room temperature may allow the oxidant to be used to effectively treat chlorobenzenes present in site ground water.

For the BTEX constituents, persulfate with iron and the combination of permanganate and persulfate was moderately effective in reducing the mass of all four compounds (i.e., greater than 67%). Applied sequentially (i.e., permanganate followed by persulfate), the test yielded a mass reduction efficiency of greater than 90% for the BTEX compounds.

Permanganate alone was ineffective in treating benzene, though the oxidant was very effective against toluene, ethylbenzene, and the xylenes in the 70-day tests.

For the non-chlorinated solvents, both oxidants were effective against 4-methyl-2-pentanone, while acetone was effectively treated by permanganate, persulfate with iron, and the sequential treatment. The combined treatment appeared to be ineffective in treating acetone.

The trends in the Day 70 data are similar to those observed with the Day 38 samples. Table 4 indicates the removal efficiencies at day 38 and day 70 for each of the test scenarios. In general, permanganate was highly effective in removing the chloroethenes, toluene, ethylbenzene, xylenes, and 4-methyl-2-pentanone (MIBK), but had only limited effect on methylene chloride, benzene, chlorobenzene, and the chloroethanes. The persulfate appeared to be significantly more effective in removing chloroethane, chlorobenzene, and benzene; significantly less effective on tetrachloroethene, ethylbenzene, and xylenes; and also had limited effectiveness on methylene chloride, 1,2-dichloroethane, and 1,1,1-trichloroethane. Combining the two oxidants (concurrently or sequentially) seemed generally to have additive but not synergistic effects, with the possible exception of effectiveness in removing 1,1,1-trichloroethane. Some improvements in the removal of methylene chloride, chloroethane, and chlorobenzene were observed with the extended duration; but, in general, the extended duration did not significantly increase removal effectiveness.

Process Development Testing with Heated Persulfate

Recent development work using distilled water spiked with various VOCs has shown that persulfate at elevated reaction temperatures (45° C to 55° C) can accomplish essentially complete destruction of all of the Constituents of Potential Concern at the MSG&S site over a 5 to 20 day reaction period. A description of this preliminary process development testing and results is provided in Attachment A.

These results could have a significant implication for the potential combined use of in-situ thermal and in-situ chemical oxidation at the MSG&S site. The introduction of sodium persulfate during in situ heating may also decrease the time and temperature of heating required to remove constituents from both the soils and ground water by

combining the effects of thermal stripping with thermally activated chemical oxidation, potentially resulting in significant reductions in both remediation time and energy use. Heated persulfate experiments using soil alone or soil slurries have not yet been completed. However, based on the results of testing with water alone, it is possible that higher reaction temperatures may result in significantly greater VOC destruction efficiencies in the presence of soils than were achieved in the MSG&S bench-scale testing that was conducted at room temperature. Additional testing would be required to establish the baseline conditions for this approach.

Sincerely,



T. Neil Peters, P.E.
Project Manager

GJS:rvs
enclosures: Tables
Attachment A

Table 1. Raw Data from 70 Day Oxidation Efficiency Tests

Supplemental MSG&S Phase IV Results

23-Jul-01

Compound	T = 0 Control		T = F Control		Permanganate		Persul. + Iron		Combined		Sequential	
	Ave. Water mg/L	Ave. Soil mg/kg	Water mg/L	Soil mg/kg	Water mg/L	Soil mg/kg	Water mg/L	Soil mg/kg	Water mg/L	Soil mg/kg	Water mg/L	Soil mg/kg
Chloromethanes												
Chloromethane	*						3.2 j**					
Methylene chloride	185	41	170	110 j	180	71	88	100	110	56	120	78
Chloroform	2.4 j, B***		1.5 j		2.3 j		76	99	1.4 j		2.8 j	
Chloroethanes												
Chloroethane	31.5		33		27	9 j	1.3 j		7.7 j		6 j	
1,1-Dichloroethane	135						0.57 j					
1,2-Dichloroethane	160	101.5	160	180	180	100	68	190	130	90	140	150
1,1,1-Trichloroethane	11	66.5	13	110 j	17	47 j	4.5 j	110	7 j	24 j	5.6 j	44 j
1,1,2-Trichloroethane							3.9 j	21 j				
1,1,2,2-Tetrachloroethane							1.3 j	24 j				
Chloroethenes												
Vinyl Chloride	3.5 j		2.5 j									
1,1-Dichloroethene		77	110	290								
1,2-Dichloroethene (total)	160	101.5	150	250								
Trichloroethene	77.5	415	62	610				49 j				18 j
Tetrachloroethene	35.5	1030	26	1,400				690		5.2 j	2.2 j	180
Chlorobenzenes												
Chlorobenzene	92	1500	85	2,000	120	940		590	54	570	26	880
Aromatic Hydrocarbons												
Benzene	110	225	110	440	120	170		5.9	30	67	7.8 j	63 j
Toluene	51.5	590	58	860				85	0.96 j			44 j
Ethylbenzene	1.7 j	59	2 j	87 j				32 j				7.9 j
Xylenes (total)	11	370	12	590				180				53 j
Non-Chlorinated Solvents												
Acetone	150 B	13	150 B		26 j, B		8.6 j, B		160 B	42	31 jB	
4-Methyl-2-pentanone	180	86	200	98 j				8.7				

* No value indicates compound not detected at Reporting Limit

** j: Estimated result. Result is less than Reporting Limit.

*** B: Compound detected in corresponding method blank

Table 2. Oxidation Efficiency Results on a Mass Basis
Supplemental MSG&S Phase IV Results
23-Jul-01

Compound	Time = 0 Control mg	Time = Final Control mg	Time = Final Permanganate mg	Time = Final Persul. + Iron mg	Time = Final Combined (a) mg	Time = Final Sequential (b) mg
Chloromethanes						
Chloromethane				0.7		
Methylene chloride	40.0	38.7	39.1	21.4	24.4	27.0
Chloroform	0.5	0.3	0.5	18.9	0.3	0.6
Chloroethanes						
Chloroethane	6.5	6.8	5.8	0.3	1.6	1.2
1,1-Dichloroethane	27.9			0.2		
1,2-Dichloroethane	37.4	38.8	39.9	20.2	29.5	33.1
1,1,1-Trichloroethane	5.1	6.2	4.8	4.5	2.1	2.4
1,1,2-Trichloroethane				1.5		
1,1,2,2-Tetrachloroethane				1.0		
Chloroethenes						
Vinyl Chloride	0.7	0.5				
1,1-Dichloroethene	3.2	31.9				
1,2-Dichloroethene (total)	37.4	38.9				
Trichloroethene	33.5	32.0		1.6		0.5
Tetrachloroethene	50.6	49.5		22.2	0.1	5.4
Chlorobenzenes						
Chlorobenzene	82.0	80.6	49.7	19.0	27.3	29.6
Aromatic Hydrocarbons						
Benzene	32.2	36.6	29.3	0.2	8.1	3.3
Toluene	35.4	39.1		2.7	0.2	1.2
Ethylbenzene	2.8	3.2		1.0		0.2
Xylenes (total)	17.8	21.1		5.8		1.5
Non-Chlorinated Solvents						
Acetone	31.6	31.1	5.4	1.8	34.3	6.4
4-Methyl-2-pentanone	40.9	44.5			1.8	

* No value indicates that the compound was not detected in the corresponding soil and water samples.

(a) Combined is a 70 day test using both potassium permanganate and sodium persulfate as oxidants.

(b) 70-day sequential tests consisted of 49 days of exposure to permanganate followed by the addition of persulfate for an additional 21 days.

Table 3. Percent Reduction Oxidation Efficiency Results on a Mass Basis

Supplemental MSG&S Phase IV Results

23-Jul-01

Compound	Percent Reduction vs. "Time = Final" Control				
	From T=0 Control	Permanganate	Persulfate + Iron	Combined (a)	Sequential (b)
Chloromethanes					
Chloromethane	NA*	NA	NA	NA	NA
Methylene chloride	3.4%	-1.3%	44.6%	37.0%	30.2%
Chloroform	37.5%	-53.3%	-5991.1%	6.7%	-86.7%
Chloroethanes					
Chloroethane	-4.8%	14.7%	96.1%	76.7%	81.8%
1,1-Dichloroethane	100.0%	NA	NA	NA	NA
1,2-Dichloroethane	-3.8%	-2.9%	48.0%	24.0%	14.7%
1,1,1-Trichloroethane	-21.4%	22.6%	27.5%	65.4%	61.5%
1,1,2-Trichloroethane	NA	NA	NA	NA	NA
1,1,2,2-Tetrachloroethane	NA	NA	NA	NA	NA
Chloroethenes					
Vinyl Chloride	27.5%	100.0%	100.0%	100.0%	100.0%
1,1-Dichloroethene	-886.5%	100.0%	100.0%	100.0%	100.0%
1,2-Dichloroethene (total)	-4.1%	100.0%	100.0%	100.0%	100.0%
Trichloroethene	4.3%	100.0%	95.1%	100.0%	98.5%
Tetrachloroethene	2.2%	100.0%	55.2%	99.7%	89.1%
Chlorobenzenes					
Chlorobenzene	1.8%	38.3%	76.5%	66.1%	63.3%
Aromatic Hydrocarbons					
Benzene	-13.7%	19.9%	99.5%	77.9%	90.9%
Toluene	-10.3%	100.0%	93.0%	99.5%	96.9%
Ethylbenzene	-11.9%	100.0%	67.4%	100.0%	93.1%
Xylenes (total)	-18.3%	100.0%	72.6%	100.0%	93.1%
Non-Chlorinated Solvents					
Acetone	1.7%	82.7%	94.3%	-10.5%	79.3%
4-Methyl-2-pentanone	-8.8%	100.0%	100.0%	96.0%	100.0%

* NA: Not applicable (compound not detected in the "Time = 0" control samples).

(a) Combined is a 70 day test using both potassium permanganate and sodium persulfate as oxidants.

(b) 70-day sequential tests consisted of 49 days of exposure to permanganate followed by the addition of persulfate for an additional 21 days.

Table 4. Percent Reduction Oxidation Efficiency Results on a Mass Basis – 38 day and 70 day

Supplemental MSG&S Phase IV Results

29-Aug-01

Compound	Percent Reduction vs. Time = Final* Control									
	Control vs T=0 Control		Permanganate		Persulfate + Iron		Combined (a)		Sequential (b)	
	38 days	70 days	38 days	70 days	38 days	70 days	38 days	70 days	38 days	70 days
Chloroethenes										
Chloromethane	NA	NA*	NA	NA	NA	NA	NA	NA	NA	NA
Methylene chloride	12.1%	3.4%	11.2%	-1.3%	17.4%	44.6%	32.7%	37.0%	39.1%	30.2%
Chloroform	41.7%	37.5%	7.1%	-53.3%	-149.9%	-5991.1%	100.0%	6.7%	100.0%	-86.7%
Chloroethenes										
Chloroethane	-1.6%	-4.8%	43.8%	14.7%	42.4%	96.1%	64.1%	76.7%	81.9%	81.8%
1,1-Dichloroethane	100.0%	100.0%	NA	NA	NA	NA	NA	NA	NA	NA
1,2-Dichloroethane	6.5%	-3.8%	0.66%	-2.9%	15.2%	48.0%	20.4%	24.0%	19.7%	14.7%
1,1,1-Trichloroethane	48.9%	-21.4%	-33.950%	22.6%	-30.2%	27.5%	-53.6%	65.4%	51.1%	61.5%
1,1,2-Trichloroethane	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1,1,2,2-Tetrachloroethane	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Chloroethenes										
Vinyl Chloride	14.5%	27.5%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1,1-Dichloroethene	-723.1%	-886.5%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1,2-Dichloroethene (total)	6.9%	-4.1%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Trichloroethene	35.5%	4.3%	100.0%	100.0%	92.1%	95.1%	96.5%	100.0%	100.0%	98.5%
Tetrachloroethene	56.1%	2.2%	90.7%	100.0%	33.9%	55.2%	91.5%	99.7%	93.2%	89.1%
Chlorobenzenes										
Chlorobenzene	52.2%	1.8%	-58.3%	38.3%	68.1%	76.5%	-50.2%	66.1%	40.9%	63.3%
Aromatic Hydrocarbons										
Benzene	12.9%	-13.7%	1.6%	19.9%	98.3%	99.5%	45.5%	77.9%	79.1%	90.9%
Toluene	46.4%	-10.3%	59.8%	100.0%	88.0%	93.0%	82.2%	99.5%	95.0%	96.9%
Ethylbenzene	57.7%	-11.9%	100.0%	100.0%	50.2%	67.4%	100.0%	100.0%	100.0%	93.1%
Xylenes (total)	56.5%	-18.3%	28.8%	100.0%	56.4%	72.6%	49.2%	100.0%	89.5%	93.1%
Non-Chlorinated Solvents										
Acetone	47.8%	1.7%	97.4%	82.7%	73.6%	94.3%	-9.2%	-10.5%	86.2%	79.3%
4-Methyl-2-pentanone	5.8%	-8.8%	98.2%	100.0%	100.0%	100.0%	99.0%	96.0%	100.0%	100.0%

* NA: Not applicable (compound not detected in the "Time = 0" control samples).

(a) Combined test using both potassium permanganate and sodium persulfate concurrently as oxidants for both the 38-days and 70-days.

(b) 38-day sequential tests consisted of 21 days of exposure to permanganate followed by the addition of persulfate for an additional 17 days;

70-day sequential tests consisted of 49 days of exposure to permanganate followed by the addition of persulfate for an additional 21 days.

Attachment A
Preliminary Process Development Testing
of Oxidation of VOCs with Sodium Persulfate

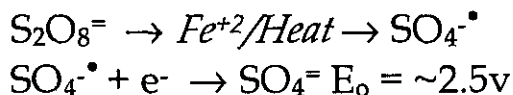
Introduction:

Potassium Permanganate (KMnO₄) has proven to be a cost-effective oxidant for the in situ chemical oxidation of VOCs, particularly chlorinated VOCs. It is, however, limited in the range of compounds that it can oxidize. In general permanganate is most effective with VOCs that contain double bonds such as the chlorinated ethenes (PCE, TCE, DCE, etc.). Permanganate will not oxidize chlorinated ethanes (1,1,1-TCA, DCA, etc.) or chloromethanes. Additionally permanganate is ineffective in oxidizing benzene and chlorobenzene, even though these VOCs contain double bonds. As a result of these limitations, ERM has been investigating alternative oxidants.

One oxidant that shows great promise for the in situ oxidation of VOCs is sodium persulfate (Na₂S₂O₈). Sodium persulfate is a soluble, strong oxidant.



It generally reacts via a free radical pathway, through the formation of sulfate radicals. This pathway requires activation of the persulfate either by catalysis with iron II or by thermal activation:



Heat activation has the potential advantage of greater free radical generation efficiency; it produces two sulfate radicals for every persulfate molecule. The iron catalysis produces one.

Oxidation Effectiveness:

ERM has been conducting research on the oxidation effectiveness of persulfate. The experiments used 40 mL sealed VOA vials. These were filled to zero headspace, and spiked with a solution of VOCs, 11,000 mg/L of sodium persulfate, and, in some cases, an iron solution. The VOA vials were sacrificed at the appropriate times and analyzed by GC/MS for VOCs by method 8260B. Appropriate controls were also run.

Table 1 presents data for the iron activation of persulfate at ambient temperature. It compares permanganate ("Perm"), persulfate alone ("Pers"), and persulfate catalyzed by iron ("Pers+Fe"). Results are given for 7, 28 and 90 days. The following observations can be made:

7 Day Results:

- Permanganate has completely oxidized the chlorinated ethenes and TEX (toluene, ethylbenzene, and xylenes) compounds. It has partially oxidized MTBE producing some t-butyl alcohol (t-BA). It has not reacted with the chlorinated ethanes, methanes, benzene or chlorobenzene.
- Persulfate alone has not reacted with any of the VOCs.
- Persulfate plus iron has completely oxidized the chlorinated ethenes BTEX compounds and chlorobenzene. It has substantially oxidized MTBE, producing some t-BA. It has not reacted with the chlorinated ethanes or methanes.

28 Day Results:

- Permanganate has further reacted with MTBE producing significant t-BA. It has not reacted with the chlorinated ethanes, methanes, benzene or chlorobenzene.
- Persulfate alone has partially oxidized the chlorinated ethenes, BTEX compounds and chlorobenzene. It has substantially oxidized MTBE, producing some t-BA. It has partially oxidized TCA and methylene chloride (MC).
- Persulfate plus iron has completely oxidized the chlorinated ethenes, BTEX compounds and chlorobenzene. It has substantially oxidized MTBE and the t-BA. It has not reacted with the chlorinated ethanes or methanes. It has partially oxidized TCA, DCA, MC and chloroform (CF)

90 Day results:

- Permanganate has further reacted with MTBE producing significant t-BA. It has not reacted with the chlorinated ethanes, methanes, benzene or chlorobenzene.
- Persulfate alone has partially oxidized the chlorinated ethenes, BTEX compounds and chlorobenzene. It has substantially oxidized MTBE, producing more t-BA. It has shows limited oxidation of the chlorinated ethanes and methanes.
- Persulfate plus iron has completely oxidized the chlorinated ethenes BTEX compounds and chlorobenzene. It has substantially oxidized MTBE and the t-

BA. It has not reacted with the chlorinated ethanes or methanes. It has partially oxidized TCA, DCA, MC and chloroform (CF).

The conclusions that can be drawn from this study are that persulfate will oxidize chlorobenzene and benzene; persulfate with iron oxidation will oxidize the chlorinated ethanes and methanes. The reaction with the chloroethanes and methanes is slow.

Thermal Activation:

Because of the slow response of the chlorinated ethanes and methanes to iron activated persulfate, a second set of experiments were conducted to look at the thermal activation of persulfate. The results are given in Table 2. The table gives data for control vials at 20, 35, 45, and 55 °C (no persulfate added) and for persulfate/iron treated vials at 20, 35, 45, and 55 °C. The tables list the actual concentrations at the different temperatures as well as the percent reduction. For the controls the percent reduction is calculated relative to the T=0 concentration. For the persulfate treated samples, the percent reduction is given relative to the control at that temperature. The following observations can be made from the data:

- At 20 °C the persulfate results are very similar to the results in Table 1. Persulfate and iron oxidize the chlorinated ethenes, BTEX and chlorobenzenes. It does not react with the chlorinated ethanes or methanes.
- At 35 °C persulfate and iron show good reactivity with the chlorinated ethanes and methanes.
- At 45 and 55 °C all the VOCs are oxidized by the persulfate in the 20-day time period (relative to the control and the T=0 concentrations).
- At 45 and 55 °C many of the VOCs are reduced in the controls relative to the T=0 concentrations. This may be due to volatile loss and potentially thermal degradation. TCA, PCE and 1,2,4-trichlorobenzene show the greatest reduction relative to the control.

The conclusion that can be drawn from this study is that heat-activated persulfate is very effective in oxidizing a wide range of VOCs. The reactivity increases with increasing temperature.

Conclusion:

Sodium persulfate expands the list of VOCs that can be effectively treated by insitu chemical oxidation. Persulfate, however, requires activation. Iron activation is effective for chlorinated ethenes, BTEX, and chlorobenzene. It does make persulfate reactive with the chlorinated ethanes and methanes but requires

long reaction times. Thermal activation makes persulfate reactive with almost all VOCs. The oxidation is fairly rapid. Increasing temperature increases the effectiveness of oxidation.

Table 2: 20-Day Heated Persulfate Oxidation Efficiency Results

Analyte	Avg. Time μg/L	Control 20°C μg/L	Control 20°C % Red. T=0	Control 35°C μg/L	Control 35°C % Red. T=0	Control 45°C μg/L	Control 45°C % Red. T=0	Control 55°C μg/L	Control 55°C % Red. T=0	Persulfate 20°C μg/L	Persulfate 20°C % Red. T=0	Persulfate 35°C μg/L	Persulfate 35°C % Red. T=0	Avg. Persulfate 45°C μg/L	Avg. Persulfate 45°C % Red. T=0	Avg. Persulfate 55°C μg/L	Avg. Persulfate 55°C % Red. T=0
Chloromethane	ND	ND		ND		ND		ND		ND		ND		ND		ND	
Methylene Chloride	18,776	18,683	0	17,416	7	16,506	12	14,725	22	19,786	-6	4,060	77	ND	100	ND	100
Chloroform	19,054	19,540	-3	18,536	3	17,094	10	15,474	19	21,156	-8	10,800	42	ND	100	ND	100
Carbon Tetrachloride	21,716	21,184	2	19,693	9	17,152	21	13,943	39	23,424	-11	ND	100	ND	100	ND	100
1,1-Dichloroethane	16,578	17,703	-7	16,859	-2	15,684	5	14,336	14	19,150	-8	576	97	ND	100	ND	100
1,2-Dichloroethane	47,078	47,257	12	39,784	15	38,010	19	34,671	26	46,730	-13	754	98	ND	100	ND	100
1,1,1-Trichloroethane	19,344	18,839	3	15,651	19	7,225	63	455	98	20,872	-11	9,510	39	ND	100	ND	100
1,1,2-Trichloroethane	25,494	26,911	-6	28,056	-10	26,386	-3	25,997	-2	26,870	0	3,262	88	ND	100	ND	100
1,1-Dichloroethene	13,660	11,065	19	8,398	39	6,731	51	4,233	69	640	94	ND	100	ND	100	ND	100
c-1,2-Dichloroethene	31,460	28,894	8	25,323	20	22,212	29	18,231	42	17,310	40	ND	100	ND	100	ND	100
t-1,2-Dichloroethene	2,776	1,907	31	1,146	59	686	75	297	89	1,304	32	ND	100	ND	100	ND	100
Trichloroethene	22,140	16,324	26	11,913	46	7,500	66	3,777	83	7,838	52	ND	100	ND	100	ND	100
Tetrachloroethene	22,798	14,572	37	6,791	70	3,036	87	713	97	8,264	42	ND	100	ND	100	ND	100
Chlorobenzene	20,242	16,367	19	14,123	30	10,868	46	7,682	62	4,946	70	ND	100	ND	100	ND	100
1,2-Dichlorobenzene	22,404	20,439	9	17,721	21	13,241	41	9,347	58	ND	100	ND	100	ND	100	ND	100
1,3-Dichlorobenzene	19,802	15,354	22	10,190	49	5,908	70	2,576	87	ND	100	ND	100	ND	100	ND	100
1,2,4-Trichlorobenzene	12,510	9,068	28	5,809	54	2,328	81	750	94	ND	100	ND	100	ND	100	ND	100
Benzene	14,348	13,316	7	12,327	14	11,084	23	9,374	35	4,558	66	581	95	ND	100	ND	100
Toluene	16,174	13,096	19	11,832	27	9,321	42	6,755	58	622	95	ND	100	ND	100	ND	100
Ethylbenzene	16,370	14,270	13	11,878	27	8,716	47	5,570	66	688	95	ND	100	ND	100	ND	100
o-Xylene	2,650	2,476	7	2,208	17	1,749	34	1,275	52	ND	100	ND	100	ND	100	ND	100
m,p-Xylene	10,010	8,269	17	6,502	35	4,519	55	2,663	73	308	96	ND	100	ND	100	ND	100

Elapsed Time: 5 Days
Persulfate: 11,000 mg/L
Iron: 500 mg/L